Role of Passive Valves & Devices in Poison Injection System of Advanced Heavy Water Reactor

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Abstract

The Advanced Heavy Water Reactor (AHWR) is a 300 MWe pressure tube type boiling light water (H_2O) cooled, heavy water (D_2O) moderated reactor. The reactor design is based on well-proven water reactor technologies and incorporates a number of passive safety features such as natural circulation core cooling; direct in-bundle injection of light water coolant during a Loss of Coolant Accident (LOCA) from Advanced Accumulators and Gravity Driven Water Pool by passive means; Passive Decay Heat Removal using Isolation Condensers, Passive Containment Cooling System and Passive Containment Isolation System.

In addition to above, there is another passive safety system named as Passive Poison Injection System (PPIS) which is capable of shutting down the reactor for a prolonged time. It is an additional safety system in AHWR to fulfill the shutdown function in the event of failure of wired shutdown systems i.e. primary and secondary shut down systems of the reactor.

When demanded, PPIS injects the liquid poison into the moderator by passive means using passive valves and devices. On increase of main heat transport (MHT) system pressure beyond a predetermined value, a set of rupture disks burst, which in-turn actuate the passive valve. The opening of passive valve initiates inrush of high pressure helium gas into poison tanks to push the poison into the moderator system, thereby shutting down the reactor.

This paper primarily deals with design and development of Passive Poison Injection System (PPIS) and its passive valves & devices. Recently, a prototype DN 65 size Poison Injection Passive Valve (PIPV) has been developed for AHWR usage and tested rigorously under simulated conditions. The paper will highlight the role of passive valves & devices in PPIS of AHWR. The design concept and test results of passive valves along with rupture disk performance will also be covered.

Keywords - Advanced Heavy Water Reactor (AHWR), Shut Down System (SDS), passive valve, poison injection, analytical model, passive safety system

1. Introduction

Following the Fukushima accident in 2011, there is an increasing need to provide systems with passive or intrinsic characteristics which would ensure the continued cooling of fuel and its containment systems. The Advanced Heavy Water Reactor (AHWR) being designed in India incorporates several passive safety systems which will enable the plant to survive potential severe accidents without fuel damage and requiring no human intervention [1]. The AHWR is a 300 MWe, vertical, pressure tube type, heavy-water-moderated, boiling light-water-cooled reactor with a 100 year lifetime. Heat is removed from the core with natural circulation of coolant during normal operation, transient and accident conditions which eliminates all accident scenarios resulting from pump failure and thus provides an inherent safety feature in reactor design [2]. Several passive systems are incorporated in AHWR in coherence with its basic design philosophy [3]. The direct in-bundle injection of light water coolant during a Loss of Coolant Accident (LOCA) from Advanced Accumulators and Gravity Driven Water Pool by passive means, Passive Decay Heat Removal using Isolation Condensers, Passive Containment Cooling System, Passive Containment Isolation System are some of the important passive features included in reactor design.

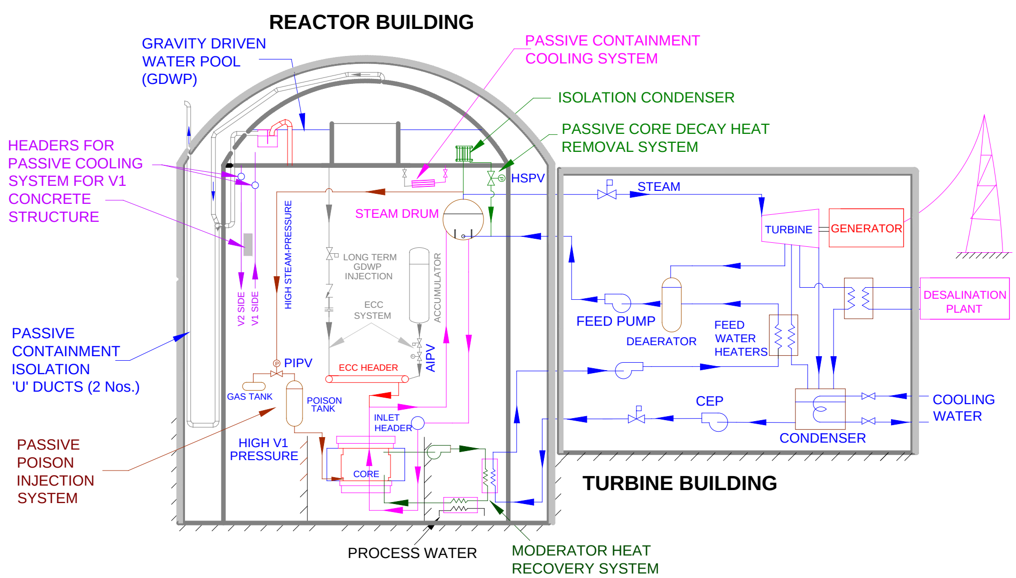

Figure 1: Passive Systems of AHWR

Another important passive safety system incorporated in AHWR is named as Passive Poison Injection System (PPIS) [4]. It is an additional safety system in AHWR to fulfill the shutdown function in the event of failure of primary and secondary shut down systems and capable of shutting down the reactor for a prolonged period of time.

The operation of some of the important passive safety systems is governed by innovative passive valves and devices like rupture disks. Based on the process and functional requirement, these valves have been named as the Hot Shutdown Passive Valve (HSPV), Poison Injection Passive Valve (PIPV) and Accumulator Isolation Passive Valve (AIPV). Since the valves used in these safety systems, do not require active power supply (i.e., electrical or pneumatic) for operation; hence known as passive valves. These passive valves have been indigenously designed and developed to suit different process requirements of individual passive safety systems. The salient features of passive valves are as follows;

- No external power – electrical or pneumatic.
- Uses process fluid energy for actuation.
- Provides regulation or isolation as per process requirement.
- Bellows sealed & bellows actuated.
- Double sealed pressure boundary.

For AHWR; some of the passive valves, as shown in Fig.1, have been designed, developed and successfully tested & demonstrated at scaled experimental facilities, including the:

- Hot Shutdown Passive Valve (HSPV) for Passive core decay heat removal system [6].
- Accumulator Isolation Passive Valve for Passive emergency core cooling system [7].
- Poison Injection Passive Valve (PIPV) for Passive poison injection system.

2. Passive Poison Injection System (PPIS)

The PPIS is an additional safety system in Advanced Heavy Water Reactor (AHWR) to fulfill the shutdown function in the event of failure of wired shutdown systems i.e. Shut Down System-1 (SDS#1) and Shut Down System-2 (SDS#2). The SDS#1 uses gravity driven shut off rods and SDS#2 has a mechanism for gas driven poison injection into the moderator for reactor shutdown. Indian 540 MWe Pressurized Heavy Water Reactors (PHWR) under operation are successfully using SDS#1 & SDS#2. These two systems are wired systems and have dependence on external source of power, thus susceptible to extreme external events or malevolent acts. On the other hand, SDS#2 and PPIS are similar in function, but use entirely independent hardware and are equally capable of performing shutdown function of the reactor. Unlike SDS#2 which acts on system control logics, PPIS actuates passively. It gets actuated due to increase in the Main Heat Transport (MHT) pressure, which in-turn opens passive valves and devices to force-inject poison into the moderator and thereby shutdown the reactor [5]. The PPIS actuation is demanded under the following conditions;

a) Station Blackout (SBO) or Class IV failure and failure of wired shutdown systems.
b) Feed water failure and failure of wired shutdown systems.
c) Loss of Regulator Accident (LORA) and failure of wired shutdown systems.
d) Loss of Coolant Accident (LOCA) with break size less than 25% and failure of wired shutdown systems.

System design objectives include actuation of PPIS during MHT pressure rise. In case of LOCA the rise in MHT pressure occurs when break size is less than 25% with failure of wired shutdown systems.

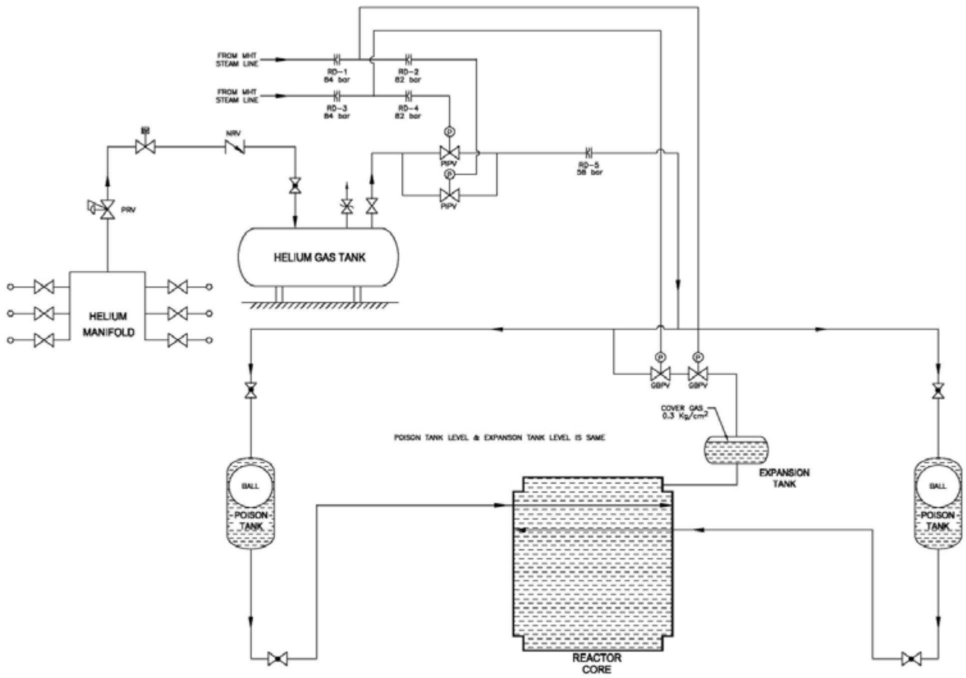

Figure 2: Process flow diagram of PPIS for AHWR

The schematic of PPIS for AHWR is shown in Figure 2. The system consists of a gas tank, poison tanks, condensate pot, rupture disks, passive valves, and helium gas cylinders with associated valves and piping. The PPIS operates on the principle of direct injection of poison (gadolinium nitrate solution in heavy water) into the moderator by means of high pressure helium.

There are eight, horizontally located, poison injection tubes inside the calandria with 120 nos. of holes along its length [8]. The liquid poison is stored in eight tanks, known as poison tanks and each tank is connected to an injection tube. The pressurized helium gas tank is connected to the poison tanks through two quick–opening, and fast-acting passive valves in parallel named as Poison Injection Passive Valves (PIPV). These valves get actuated by passive means at actuator pressure of 84 bar and above. The actuator of each PIPV has a connection from MHT steam line individually. A set of two rupture disks (RD) in series are provided on each steam line to PIPV actuator to avoid the inadvertent actuation of PPIS due to failure of one RD. Even if spurious or premature bursting of both RDs take place, passive valves do not allow PPIS actuation unless the MHT pressure reaches the alarming value. Since PIPV is having metal to metal seat and large differential pressure acts across it, there might be very small leak path through its seat, over a long period of time. To prevent mixing of poison to calandria due to PIPV seat leakage, rupture disk RD-5 is provided.

Poison tanks are located in such a way that the 100% level in the poison tank is same as moderator level in calandria. Under normal conditions, the poison solution and moderator are separated by a chemical interface known as 'poison moderator interface' (PMI). As observed experimentally, the PMI movement towards calandria is quite small for required poison concentration. Under poised condition all the poison tanks are in direct communication with moderator system so that equal pressure is maintained in calandria and poison tanks. This is achieved through two quick-closing fast-acting passive valves in series named as Gas Balance Passive Valves (GBPV) connected between poison tanks header and moderator cover gas.

When both SDS#1 & 2 fail, on demand, the MHT pressure increases. The rise in MHT pressure to 84 bars, bursts the rupture disks and actuates the PIPV to open. The high pressure helium at gas tank forces the poison tank solution into the calandria through the holes in the injection tubes and shutdown the reactor. On PPIS actuation, before PIPVs open, the GBPVs which are in line connecting poison tank header and moderator cover gas, are closed.

3. Passive Valves and Devices in PPIS

The most important feature of PPIS is that it's a complete passive system that works even in the absence of power supply or pneumatic supply. This is achieved by incorporating passive valves such as Poison Injection Passive Valve (PIPV) & Gas Balance Passive Valve (GBPV) and passive devices such as rupture disks in the system. These valves and devices are self acting type, require no external energy, i.e. neither air nor electric supply for actuation. The process pressure itself actuates passive valves and devices. This feature makes the PPIS functioning independent of external systems such as compressed air supply or electric power supply and thereby providing inherent safety feature in line with reactor design philosophy.

4. Design and Development of Poison Injection Passive Valve

Towards the development and implementation of PPIS for AHWR, a 65 NB Poison Injection Passive Valve (PIPV) shown in Figure 3, has been indigenously designed and developed. The valve has been rigorously tested for its functioning under simulated process conditions. The multi-ply metallic bellows used in some of the valves have been tested at rated conditions at Bellows Test Facility [9].

Figure 3: 65 NB PIPV

4.1 Role of Poison Injection Passive Valve (PIPV)

PIPV is a normally closed (NC) type valve. During normal reactor operation, the MHT pressure will be 70 bar and helium gas tank will be pressurized to 80 bar. The PIPV will remain closed acting as a passive isolation device between gas tank and poison tank. In abnormal conditions; with rise in steam pressure to 84 bar, rupture disks (RD-1, RD-2 & RD-3, RD-4) will burst and steam pressure will actuate the PIPV to open. The opening of passive valve will inject poison into the moderator.

The developed 65 NB Poison Injection Passive Valve (PIPV) is a self-acting valve with a bellows actuator requiring no external energy, tight closing, spring loaded, single ported valve with pressure balancing by means of stainless steel bellows.

5. PIPV Testing

To study the functional performance of the valve under simulated process conditions a test set up was designed & fabricated. The 65 NB PIPV was rigorously tested at this test set up. After successful completion, the PIPV was tested at an experimental facility of PPIS at simulated conditions. Following are the important objectives for testing of PIPV;

i) Valve functional performance at rated conditions.
ii) Valve performance at different inlet and outlet pressures conditions.
iii) Opening time of the valve.
iv) Valve dynamic performances i.e. travel vs. time measurement at rated conditions.

6. PIPV Test Setup

The test setup with installed PIPV is shown in Figure 4. PIPV actuator, through a condensate pot, is connected to another Nitrogen gas tank, simulating MHT pressure. The process medium for

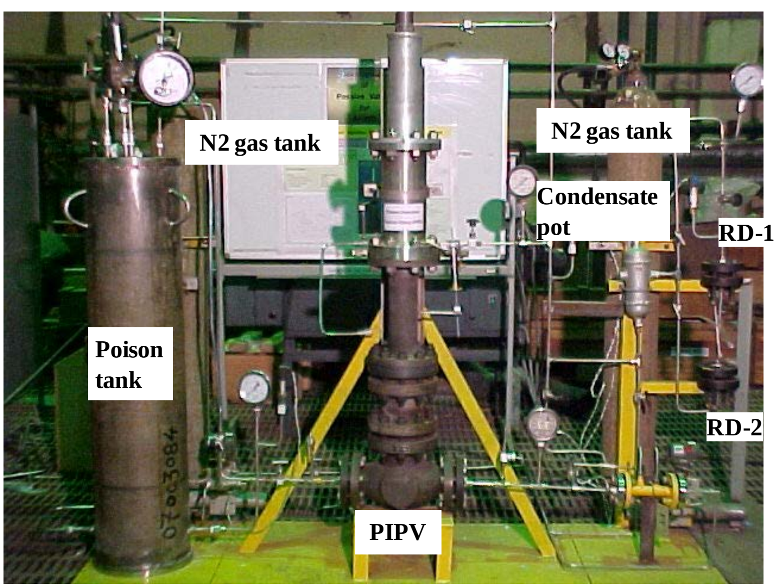

Figure 4: PIPV test setup

PIPV actuator in AHWR application will be water and condensate pot will provide the isolation between MHT steam & actuator. On rupture disks bursting, the gas pressure will actuate PIPV to open. The rupture disk RD-3 is used to prevent unexpected seepage of PIPV upstream water in case there is a seat leak developed after long usage of the valve. With PIPV open and water tank pressure more than the RD-3 burst pressure, tank water will pass through PIPV to drain simulating high-pressure poison injection.

7. Experiments and Results

7.1 PIPV Opening & Closing Characteristics

To generate the valve opening & closing characteristics, upstream and downstream pressure to valve were kept at atmospheric condition. The pressure in actuator was gradually increased and valve stem movement by Linear Variable Displacement Transducer (LVDT) was recorded. The extracted data from experimental results are graphically shown in Figure 5.

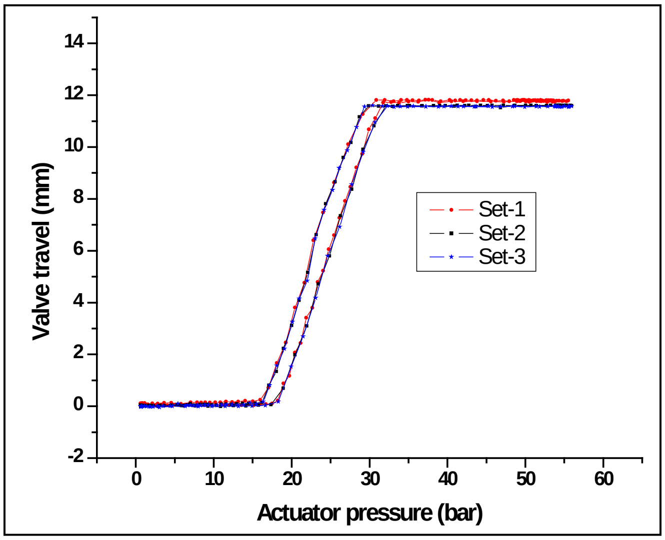

Figure 5: PIPV characteristics

7.2 Process Simulation Experiments without Rupture Disks

These experiments were conducted without rupture disks RD-1, RD-2 & RD-3 with respective valves to generate valve performance parameter data so that optimum inventory of rupture disks can be used for experimental purpose. The initial upstream and downstream pressure of PIPV was maintained respectively at 80 bar and 2 bar. The PIPV actuator pressure was gradually increased till valve opening was observed with large pressure breaking sound and downstream pressure also increases. After full opening of valve as observed by LVDT reading, the actuator pressure was gradually decreased to zero to close PIPV. Similar experiments were carried out for different upstream pressure of 60, 73 & 84 bar with downstream pressure of 2 bar. A typical process parameters trend recorded with experiment at 80 bar upstream pressure is shown in Figure 6.

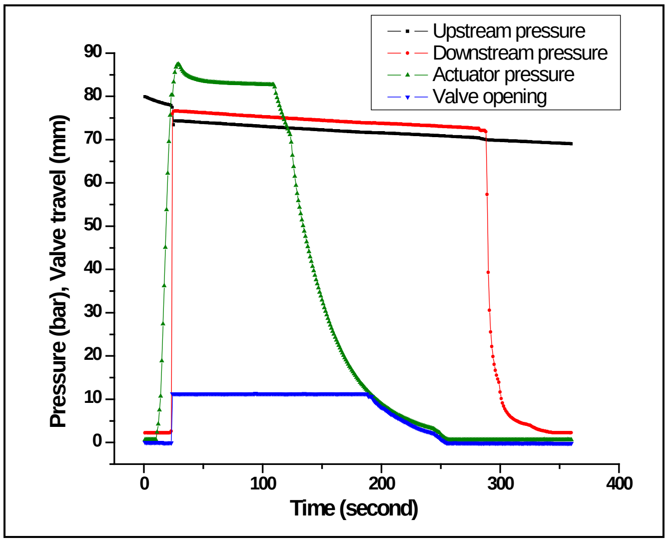

Figure 6: Experimental result with PIPV upstream pressure 80 bar

7.3 Process Simulation with Rupture Disks in Line

After obtaining successful experimental results without rupture disks testing was carried out with RD-1 & RD-2 in line to have actual process simulation as in AHWR PPIS scheme. RD-3 was not installed as it is meant for PIPV seat leakage only over a long period of time in PPIS.

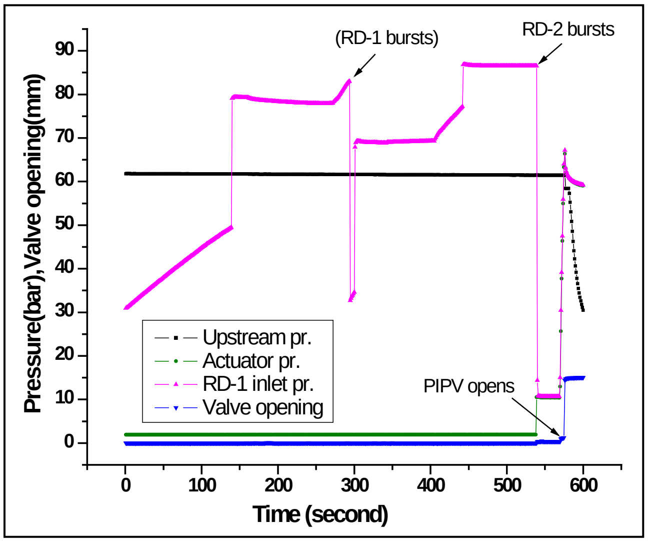

Figure 7: Experimental results with rupture disks in line

In test setup as experiments are carried out for a very short period of time, simulation with RD-3 in line is not required. The burst pressure of installed RD-1 & RD-2 was 80 and 82 bar respectively. With PIPV upstream & downstream pressure at 60 bar & 2 bar respectively, pressure at upstream of RD-1 was increased till both RD-1 & RD-2 burst open and gas pressure directly acts on PIPV actuator. The process parameter trend recorded during the experimentation is shown in Figure 7.

7.4 Valve Opening Time Measurement

Experiments were carried out at different upstream pressure of 60, 70, 73 & 84 bar with downstream pressure at 2 bar. The actuator pressure and valve stem travel by LVDT were recorded in a high speed Oscilloscope-Recorder. For a set of PIPV upstream and downstream pressure, the actuator was pressurized till valve is fully opened. As shown in digital oscilloscope screen shot Fig.8, on actuator pressure reaching 84 bar, the valve suddenly opens and LVDT output goes to + 3.57V. The sudden rise in LVDT output provides valve opening time of 400 milli-seconds.

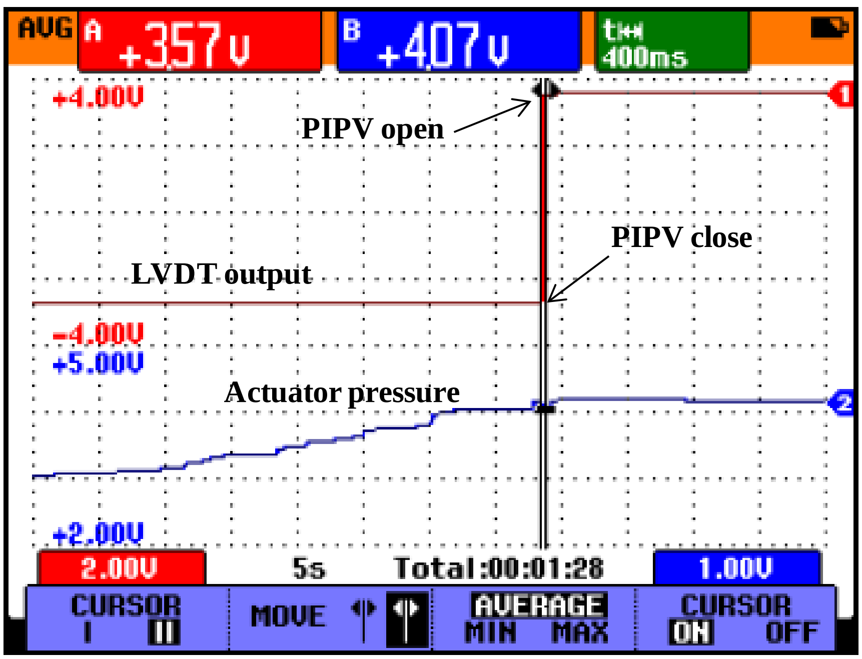

Figure 8: Experimental result for response time measurement

7.5 Test at PPIS Experimental Facility

An experimental facility of PPIS with scaled down calandria model (1/6th) was designed to demonstrate the poison injection phenomenon. The PPIS facility consists of a gas tank, rupture disks, a poison tank, PIPV, solenoid valves, and scaled down model of calandria with instrumentation as shown in Figure 9. The 65 NB PIPV was installed in parallel to a solenoid (active) valve. During PPIS experiments this solenoid valve is kept closed. The burst pressure of 25 NB size rupture disks RD-1 & RD-2 were 84 bar & 82 bar, as required in AHWR. The installed PIPV in PPIS experimental facility is shown in Figure 10. Nitrogen cylinder was used to pressurize the PIPV actuator through a condensate pot. The initial poison injection experiments have been conducted to maximum gas tank pressure of 30 bar due to design limitation of acrylic calandria model. The process parameter trend during experiments with bursting of rupture disks is shown in Figure 11.

Figure 10: PIPV installed at PPIS experimental facility

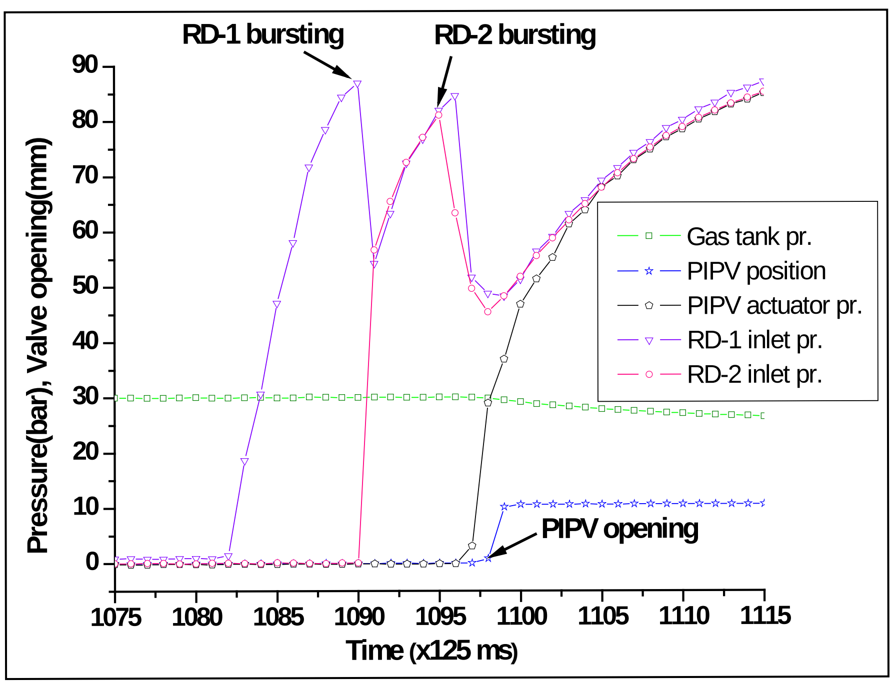

Figure 11: PPIS experiment at 30 bar gas tank pressure with rupture disk

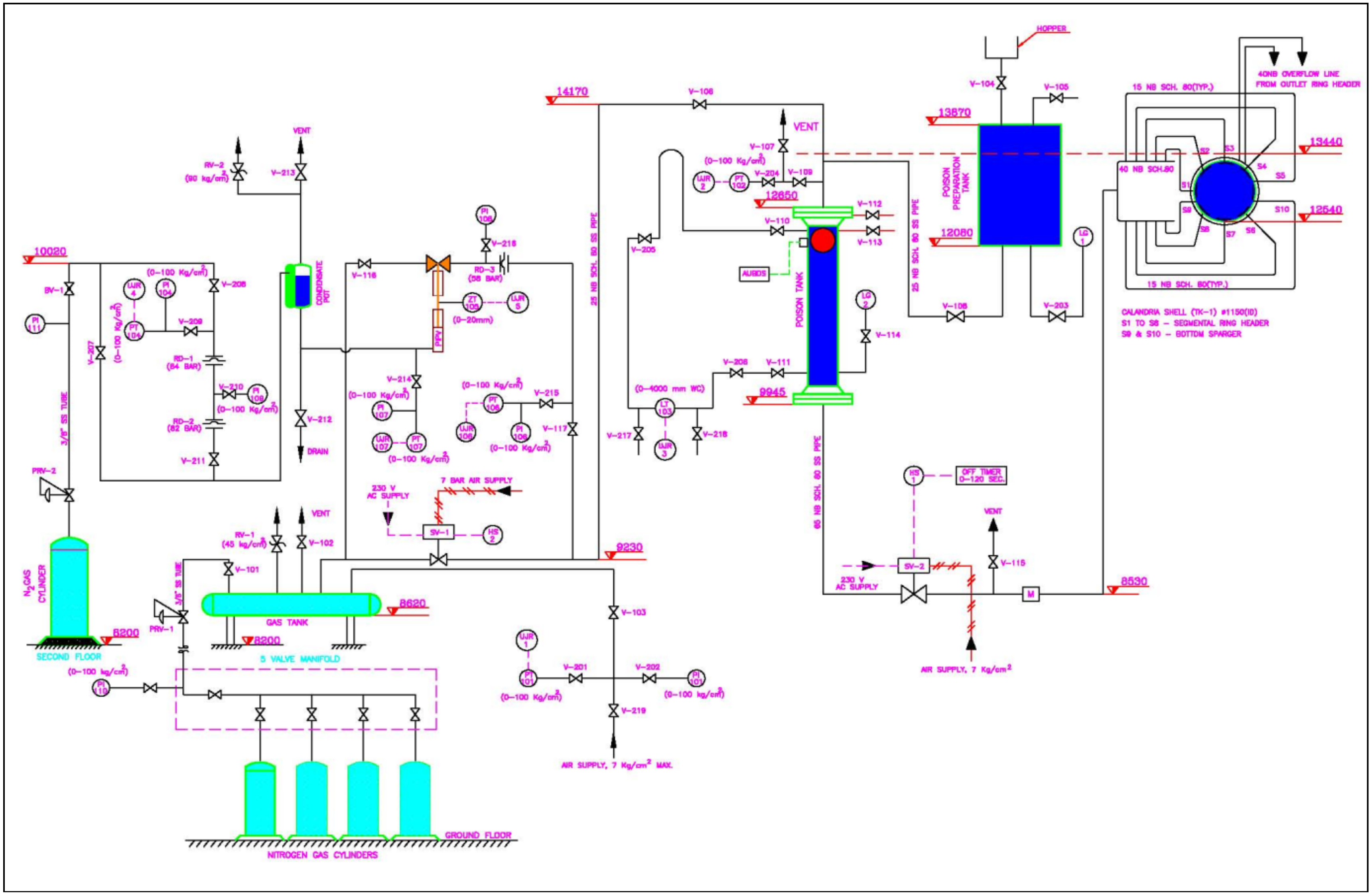

Figure 9: PPIS experimental facility

8. Analysis and Discussion

The above experimental results lead to the following inferences.

8.1 Linearity and Hysteresis

The opening & closing of PIPV is dependent of actuator pressure, upstream and downstream pressure. The results obtained in Figure 5 show a trend between actuator pressure and valve travel with both upstream and downstream pressure kept at zero. It is found that for change in actuator pressure of 15 bar the full travel of the valve occurs and the maximum non-linearity of 10 % is obtained over full range travel. The analysis also shows a hysteresis of 16 % in valve opening and closing. From the valve operation point of view, the good linearity and hysteresis is not essential as this valve will be used for shutdown purpose which requires full opening of the valve in 500 milli-seconds to achieve target of 2 seconds, for complete poison injection. However, based on the experimental analysis, if required, valve trim design can be fine tuned and linearity can be improved with better quality of metallic bellows and other components.

8.2 Repeatability

More than 100 operations of PIPV were conducted during experimental run. A good repeatability in valve opening at specified actuator pressure was observed with reference to same upstream and downstream pressures conditions. In general it was found to be +/- 5% band, which is acceptable.

8.3 Process Simulation

As per the basic design in AHWR application, PIPV upstream (inlet) will be connected to gas tank and downstream side (outlet) to top of the poison tank; which is at cover gas pressure. The gas tank will be kept pressurized at 80 bar. As per process requirement; experiments were conducted at varying PIPV upstream pressure 60 to 84 bar and downstream pressure maximum upto 2 bar. Depending on the upstream pressure, PIPV opening was observed at different actuator pressure. Similar graphical trends observed in all experiments confirm good repeatability of PIPV operations. Some of the experimental data for PIPV opening are given in Table – 1 below;

Table – 1: PIPV opening at different upstream and downstream pressure

PIPV upstream pressure (bar)	PIPV downstream pressure (bar)	PIPV opening actuator pressure (bar)
61.91	1.57	59.85
62.86	1.04	60.39
73.67	1.35	72.07
81.86	1.63	80.22
83.30	1.66	81.47

The above data clearly indicates that the passive valve opening by actuator pressure depends on the difference between upstream and downstream pressure to the valve; which is in accordance with the design basis of PIPV.

Experiments by bursting two rupture disks RD-1 & 2 (burst pressure of 80 bar and 82 bar respectively) demonstrate the PIPV operation in reactor application. As RD-1 & 2 isolates the PIPV actuator from pressurizing source i.e. nitrogen cylinder, the increase in actuator pressure is observed only after bursting of both these rupture disks. The bursting of RD-1 & RD-2 occurs at 83 bar and 86 bar respectively as shown in Fig. 7. The dip in RD-1 inlet pressure after bursting of RD-1 & RD-2 is due to limited nitrogen cylinder gas volume and sudden extra volume seen after RDs bursting. This experiment was conducted with upstream pressure of 62 bar and downstream pressure of 1.4 bar. After bursting of RD-1 & 2, the PIPV opening was observed at actuator pressure of 60 bar.

8.4 PIPV Response Time

The response time of PIPV (NC) is defined as the time taken for the valve to change from its full close position to full open position, once required actuating pressure is applied. Response time is measured by LVDT movement attached to the stem of the valve. The high speed Oscilloscope-recorder records the LVDT output from valve full close to full open position. As shown in Fig 8, the measured opening time at rated 84 bar upstream pressure was found to be 400 milliseconds which meets the system requirement. However as shown in Fig.11, the valve opening time is much higher at relatively lower pressure such as 30 bar pressure.

8.5 Functional Testing of PIPV at PPIS Experimental Facility

The functional testing of PIPV along with two rupture disks of 84 and 82 bar, in PPIS experimental facility is demonstrated in Fig.11. The bursting of two rupture disks RD-1 & 2 having tagged burst pressure of 84 bar and 82 bar respectively; took place at 86 bar and 84 bar respectively in 250 ms. This initiated the poison injection by opening the passive valve in 400 ms as expected. The dip in RD-1 inlet pressure after bursting of RD-1 is due to limited discharge capacity of regulator used with nitrogen cylinder. After bursting of RD-1 & 2, the PIPV opening was observed at actuator pressure of 37 bar. This opening pressure is actually corresponding to gas tank pressure of 30 bar. As mentioned earlier; due to usage of Perspex calandria model; the gas tank pressure was limited to 30 bar. The PPIS experimental facility is being modified to take up further experiments upto rated pressure of 80 bar.

9. Conclusion

The Passive Poison Injection System (PPIS) of AHWR does not depend on external source of power or human actions for successful operation and thus results in a reactor design less vulnerable to extreme external events and malevolent acts, thereby providing adequate protection against release of radioactivity outside the plant environment.

Successful development of these innovative passive valves for Passive Poison Injection System (PPIS) of AHWR; has added multifold strength into reactor safety systems. The quick opening characteristics of the order of 400 milliseconds for these valves, has made them apt for poison injection system of the reactor. The valve design is such that it uses mainly proven passive components like spring and bellows and does not use any non-metallic components like gaskets, O-rings, thus providing higher reliability & improved performance.

10. References

1. P.K. Vijayan, M.K. Dhiman, P.P. Kulkarni, M.T. Kamble, A.K. Nayak, K.K. Vaze and R.K. Sinha, 'AHWR Analysis for the Post-Fukushima Scenarios', 22nd National and 11th International ISHMT-ASME Heat and Mass Transfer Conference 2013, IIT Kharagpur, India.
2. R.K. Sinha and A. Kakodkar, 'Design and development of the AHWR – the Indian thorium fuelled innovative nuclear reactor', Science Direct, Nuclear Engineering and Design, 2006.
3. A.K. Nayak and R.K. Sinha, 'Role of Passive Systems in Advance Reactors', Science Direct, Progress in Nuclear Energy 49, 2007.
4. M.K.Sapra, S. Kundu, P. K. Vijayan, K. K. Vaze and R. K. Sinha ; Managing Accidents by a Novel Passive Shutdown System in Advanced Heavy Water Reactor ; Symposium on "Severe Accident Analysis Management (SAAM-2013) at IIT-K on 1-4th Feb 2013.
5. M.K.Sapra, A.Kansal, S.Kundu, B.S.V.G.Sharma, D.Saha & R.K.Sinha; "Passive Poison Injection System (PPIS) – an Engineered Safety System of AHWR"; 4th National Conference on Nuclear Reactor Technology (NRT-4), 4-6 March, 2011 at TSH, Anushaktinagar, Mumbai.
6. M.K.Sapra, S. Kundu, A.K. Pal & B.S.V.G. Sharma, 'Functional and Performance Evaluation of 28 Bar Hot Shutdown Passive Valve (HSPV) at Integral Test Loop (ITL) for Advanced Heavy Water Reactor (AHWR)', BARC report, 2007.
7. M.K.Sapra, S.Kundu, A.K.Pal, B.S.V.G. Sharma, D. Saha and R. K. Sinha, 'Design, development and testing of 25 NB size Accumulator Isolation Passive Valve (AIPV) for Advanced Heavy Water Reactor (AHWR)', BARC report, 2010.
8. A.K.Kansal, S.Kundu, M.K.Sapra, N.K.Maheshwari & P.K.Vijayan, 'Design Information Report (DIR) for Passive Poison Injection System of AHWR', 2012.
9. A.K. Dureja, M.K. Sapra, R.P. Pandey, P. Chellapandi, B.S.V.G.Sharma, J.N.Kayal, S.C. Chetal, R.K.Sinha, 'Design, analysis and shape optimization of metallic bellows for nuclear valve applications, Transactions SMiRT 21, November, 2011, New Delhi.