Facility for testing Innovative Safety Mechanism in Ventilation System of Nuclear Reactor Containment

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ABSTRACT

Nuclear reactors ventilation systems will have penetrations through outer containment for communication with atmosphere. The ventilation system should be designed to provide slightly negative pressure inside containment than outer atmosphere. However under accidental conditions such as Loss of Coolant Accident (LOCA), the containment pressure builds up and the ventilation system shall provide Isolation of Containment from atmosphere, so as to prevent radioactive release to atmosphere. An innovative pressure seal mechanism in venting system to create differential pressure seal is being tested in an Experimental Facility.

The paper provides with an introduction on how the safety mechanism is differentiated from existing system, the test facility with Instrumentation and controls employed, allied instrumentation provided on the system, the selection criteria for instrumentation and control components, their performance and overall response time during experimentation. The measures taken to improve upon the overall response time of system as per the experimentation requirement are also highlighted.

Keywords: LOCA, Containment, PWM, Ventilation duct, Profile controller, Control Valve, Electro-pneumatic positioner, dead band

INTRODUCTION

At present the operating Nuclear Reactors have venting systems designed to provide slightly negativepressure inside containment than outer environmental atmospheric pressure. The ventilation system comprises of Fans, Blowers, filters, Butterfly Control valves, Dampers, ventilation ducts, stack etc. A Typical Containment Ventilation and Cooling system employed in Nuclear Reactor is shown in Fig.1. In the event of Accidental conditions such as Loss of Coolant Accident, the reactor building pressure increases and methods to mitigate releaseof radioactive waste into outer atmosphere and thereby isolating the containment from communication to atmosphere is most important safety mechanism in any Nuclear Reactor. On excessive steam/vapour coming out of reactor building, the vapour gets condensed on vapour suppression systems and the air with fission products filtered, processed and released through stack. However if the pressure exceeds beyond a level, the containment gets isolated from external atmosphere by closure of damper control valves.

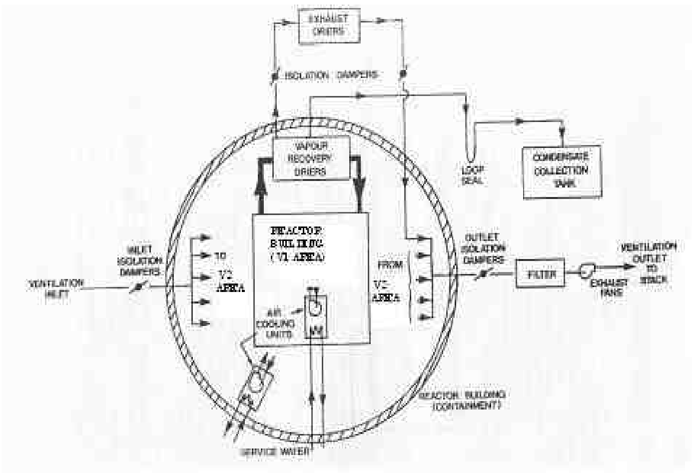


Fig.1 Typical Containment Ventilation and Cooling System

To accomplish the above referred safety objectives, today's operating reactors employ active systems, where by upon increase of reactor building pressure, interlocks will be provided to close control valves in the ventilation system. It may be noted that the closure of control valves should be done in a shortest possible time say in few seconds. The active system interlock operation requires electrical power supply as also solenoid valves, transmitters etc.

An innovative pressure seal mechanism accomplishes the above safety requirements. The mechanism does not require electricity and is purely based on natural mechanism. The mechanism involves modifying the suction and exhausts vent lines in 'U' shaped form.

The development of passive containment systems for advanced nuclear reactor systems such as Advanced Heavy Water Reactor (AHWR) requires process instrumentation and controls catering to the needs of safety. It should be adequate to monitor, control and contain the release of radioactive substances to the atmosphere during normal operating and accidental conditions. In Advanced Heavy Water Reactor (AHWR), which is being designed at BARC, many passive safety systems have been incorporated. In order to study the effectiveness of instrumentation and controls in one of the passive safety systems called Passive Isolation System of AHWR, an experimental set up has been erected at BARC.

SYSTEM DESCRIPTION

Fig.2 provides schematic of Passive Containment Isolation System of AHWR. The system is meant for study on the effectiveness of isolation where the isolation of containment with water tank (referred to as V1 volume of primary containment) discharging the flow under pressurized conditions into ventilation duct ('U' tube arrangement) and outlet open to atmosphere is formed. On reactor building pressure increase beyond a value, the water in the tank gets pushed into U-tube duct and provides a seal inside U tube. The U-tube duct extends from base ground level to stack. As such u-tube seal accomplishes passively the task of isolation without complex interlocks and electricity.

AHWR (Advanced Heavy Water Reactor) development in Indian atomic energy program has many passive safety features. The passive containment isolation is one of the passive systems for which exhaustive studies were carried out to meet the objectives set for such isolation systems. The reliability assessment of Passive containment system is well documented in reference[5]. An experimental facility to study the passive containment isolation is set up to understand the behavior of process and instrumentation responses to the occurrence of Loss of coolant accident (LOCA) conditions.

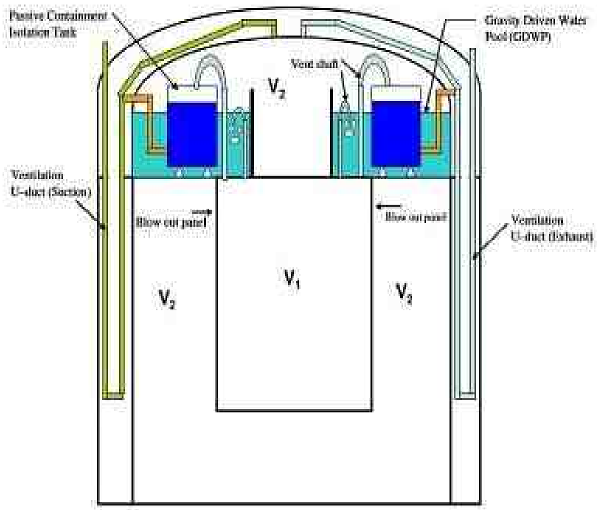


Fig.2 Schematic of Passive Containment Isolation System

INSTRUMENTATION SCHEME

The nuclear reactor containment systems, in general have primary containment, secondary containment and other ventilation systems. In the event of LOCA, the containment gets pressurized which acts on the isolation tank water surface and forces the water down and establishes water seal in the ventilation ducts isolating the containment and environment.

Fig.3 Provides the schematic of Instrumentation scheme of the Experimental test Facility. The test set up has three tanks namely T-1(Water tank) forming GDWP tank, T-2 (Air tank) is used for pressurization of tank T-1. Also T-3 (Air Tank) is to introduce air into Exit pipe simulating V2 pressure rise on accidental conditions.

For simulation of Pressure transient for rise of V1 region pressure acting on Water tank of GDWP, control valve PCV-1 Control Valve with Electronic valve positioned combination is used.

The V1 pressure is sensed by PT-1 Pressure transmitter. PRC-1 is pressure recording Controller and it has a variable set point set by Profile Controller.

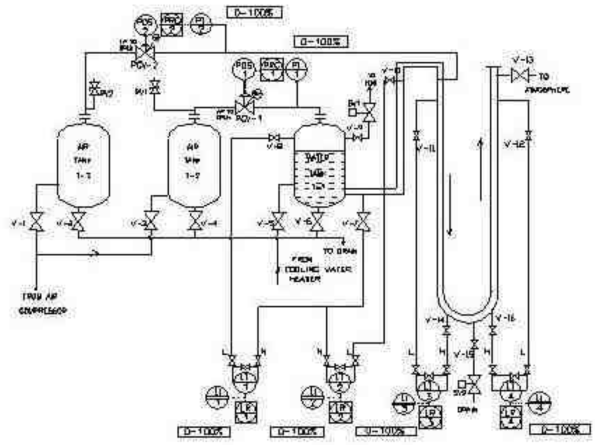


Fig.3 Schematic of Instrumentation Scheme of Test Facility.

The simulation of Pressure of V2 region on Exit pipe as shown in instrumentation diagram is through use of Control Valve PCV-2. Pressure transmitters PT-1 and PT-2 provide Pressure measurement of V1 and V2 pressure. As shown in Fig.1 the Ventilation ducts are 'U' shaped and the test facility also has U-shaped Pipe representing the duct.

Apart from the pressure instrumentation, the Water tank level is measured by Level transmitter LT-1, Level measurement in Exit pipe by LT-2, Level measurement in U-tube duct by LT-3 & LT-4 as depicted in fig.3.

The Snap shot of test Facility was shown in Fig.4.

Fig.4 Snap shot of Test Facility

As can be seen from the requirement of Containment Isolation, the simulation of pressure transient play a vital role to validate the safety mechanism conceived.

The Paper mainly discusses the instrumentation aspects in simulation of pressure rise and the factors contributing to its performance. To accomplish the pressure transient, electronic smart pressure transmitter, a profile controller, a single acting diaphragm operated control valve and an electro pneumatic valve positioner were used. As the transient is to be simulated and to obtain optimal performance the selection of Control valve, Valve positioner with good response is needed. The block diagram of instrumentation required for simulation of Pressure transient are given in Fig.5.

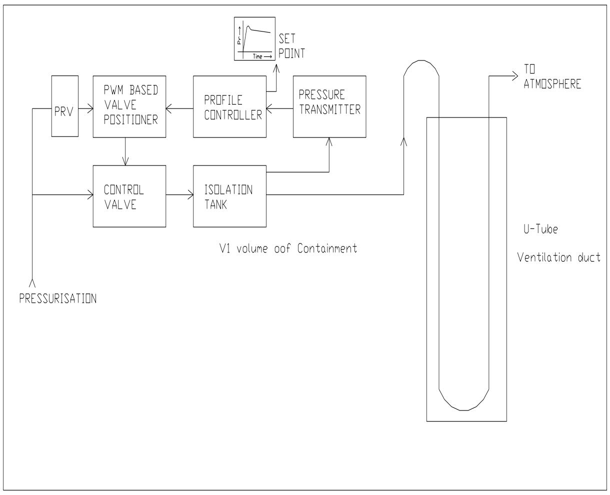


Fig.5 Set up for studies on Passive Containment Isolation

Of interest to the instrumentation engineer in the development of system for studies on containment isolation are

1. Simulation of pressure transient signal for the set up under development
2. Selection of Control valve
3. Selection of valve positioner to improve the response
4. Data acquisition aspects for recording
5. Overall system performance evaluation.

SIMULATION OF PRESSURE TRANSIENT

In order to test the safety mechanism conceived for Containment Isolation through passive means, the test facility should simulate the same conditions as in Reactor operating and accidental conditions. As per the data available from existing literature, for accidental conditions the containment pressure reaches a maximum in about 7 to 8 seconds. The mechanism should therefore act in such a way to spill water into U duct in about 4 to 5 seconds thereby creating pressure differential to isolate containment from atmosphere. The pressure transient expected of the set up is shown in Fig.6. An estimate of 4 seconds duration with a pressure rise of 200 KPa is chosen based on the preliminary design.

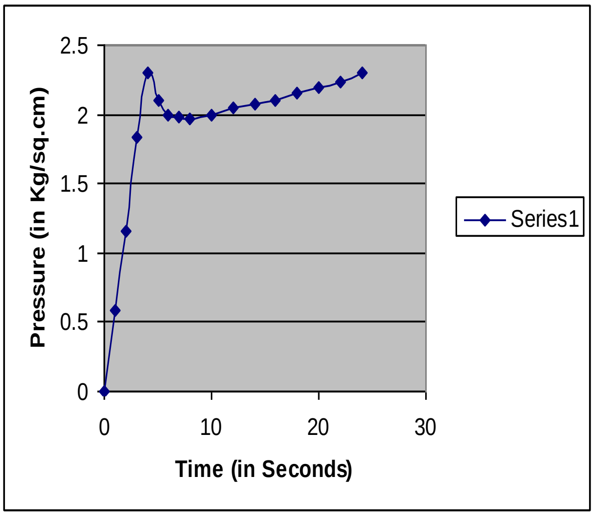


Fig. 6 Expected pressure transient for studies on containment isolation

The conventional PID controllers used to control the final control element in a continuos manner with the set point fixed and an error signal generated based on the difference between set point and process value cannot be employed. As such a profile controller, wherein the expected pressure transient is fed as a set point is considered.

The profile controller contains a set point programmer, where program can be set up as per profile in which the set point varies in a pre determined way over a period of time.

In the present case, the flexibility to set the set point in the profile controller is used to program the expected pressure profile. The program is divided into a flexible number of segments-each being a single time duration and contains details of each profiled set point. The pressure signal as shown in the fig.2 above was divided into 4 programs and each program on an average catering to about 4 segments was programmed in the profile controller.

The table illustrating the set point programming of profile controller is given in Table-1.

		Table:1	
	Time to target	Cumulative time	Target
	(in seconds)	(in seconds)	(in Kg/sq.cm)
Program1			
segment1	1	1	0.58
segment2	1	2	1.16
segment3	1	3	1.84
segment4	1	4	2.3
Program2			
segment1	1	5	2.1
segment2	1	6	2
segment3	1	7	1.98
segment4	1	8	1.97
Program3			
segment1	2	10	2
segment2	2	12	2.05
segment3	2	14	2.08
segment4	2	16	2.1
Program4			
segment1	2	18	2.15
segment2	2	20	2.2
segment3	2	22	2.23
segment4	2	24	2.3

SELECTION OF CONTROL VALVE

The essential requirement in selection of control valve was to provide the required flow for the duration thereby spilling of water into the U-tube. The tank capacity and sizing of outlets were taken care of by process engineers. The isolation tank will be filled initially with water up to 30% of tank volume.As quick response is envisaged for simulation of transient , the control valve should have tight shut off. Also the valve travel should match the characteristics of the transient intended. Accordingly the tight shut off, a single acting diaphragm operated control valve (50NB, 300 Psig) was selected to provide tight shut off having a Cv of 22.2 with equi- percentage characteristic and valve travel of 28 mm for fully close to fully open positionwas selected. It may be noted that the installed characteristics will provide required fast action for equi percentage Valve. Also to meet fail safe ideology Air to open, spring to close type of valve is used in the set up.

SELECTION OF VALVE POSITIONER

In order to improve the speed of response and to overcome friction of the control valve, the valve positioner is used. Over the years, pneumatic actuators are extensively used in industrial automation only in the open loop control mode i.e for 'pick and place' positioning problems{1}, with simple on/off solenoid valves to control their motion. Pneumatic actuators are subjected to high friction forces, dead band (due to friction), and dead time (due to compressibility of air). These non-linearities make accurate position control of a pneumatic actuator difficult to achieve. Considerable amount of research has been made by researchers [2]-[4] to implement on/off solenoid valves for the position control of pneumatic actuators and were successful in addressing smooth actuator motion in response to step inputs. To take advantage of of the use of on/off feature of solenoid valve in reducing dead band, an electro pneumatic positioner based on above principles was selected.

Brief details of electro pneumatic positioner employed is as shown in the fig.7. The Electro pneumatic positioner receives the current signal 4-20 ma from the electronic controller. With this input the positioner regulates the high pressure air supply to the final control element to give a corresponding displacement. This position control unit operates on the Pulse Width modulation (PWM) principle. The input signal is conditioned and given to a precision instrumentation amplifier. Also the feedback element is conditioned and given to precision instrumentation amplifier. Depending on the difference in these values (desired position and actual position) the relays are driven by pulse width modulation to operate the solenoid valves. The electro pneumatic positioner moves the control valve stem to the desired position by means of high pressure air supply providing the necessary power and speed of operation.

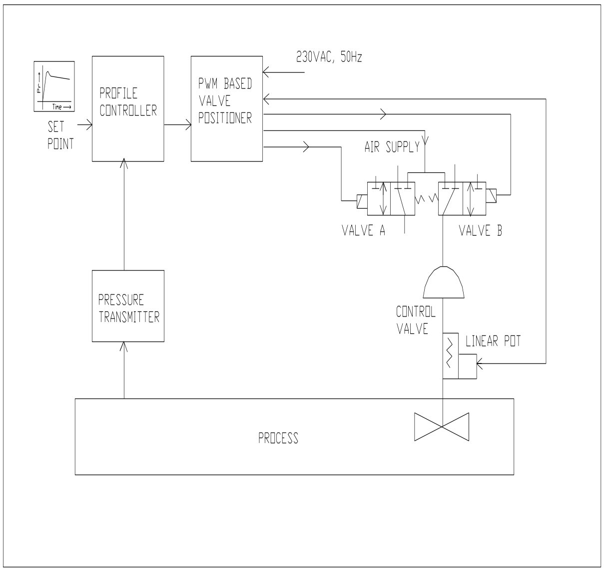


Fig.7 Electro-pneumatic Valve Positioner with on/off solenoid valves

PRICIPLE OF PWM REALIZATION

When using on/off solenoid valves to control the position of the stem, the positioner output must be resolved into the individual pulsing of the two valves A and B. Author T. Noritsuru [4] in his paper used linear pulse width modulation (PWM) scheme to control solenoid valves for pneumatic actuators. The principle underlining the control of solenoid valves is through the adjustment of duty cycle of the valves A and B. the minimum possible duty cycle, where the duty cycle of either valve A or B is not allowed to fall below this value and the valve still responds is given by

$$d_{min} = (T_{vr}/ T_{pwm})\ 100\% \qquad (1)$$

Where T_{vr} is the valve response time and T_{pwm} is the PWM period. Once either valve A or B is set at dmin, the duty cycle of the remaining valve is increased at twice the slope to maintain a linear output/input relationship. It is sufficient to understand that the PWM based valve positioner employing on/off solenoid valves works on the duty cycle concept. The positioner employed in the present set up working under the above principles has dead band approximately of 2%.

The principle of the PWM signal realization is illustrated in the fig.8. The desired PWM signal can be realized by comparing the continuos control signal and a high frequency carrier wave[4]. The carrier wave is usually a high frequency tooth wave with the period T. The frequency and amplitude of the carrier wave must change faster than those of the continuos signal.

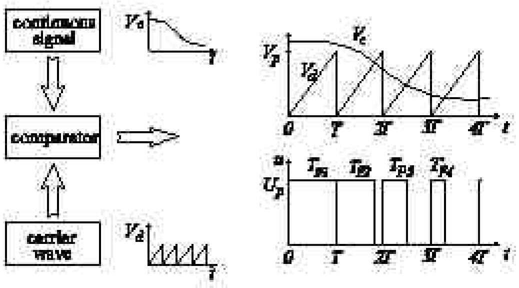


Fig.8 Principle of PWM Realization

For the case when rise and fall times of the pulses are negligible, then the mathematical description of the PWM signal can be given by the relation:

$$U_{PWM}(t)=\begin{cases}U_P, & V_t(t)\geq V_d(t)\\ 0, & V_t(t)\prec V_d(t)\end{cases} \qquad (2)$$

With

$$V_d(t)=\left[t-(j-1)T\right]V_P/T, \text{ for } (j-1)T\leq t\prec jT \qquad (3)$$

j =1,2,…..n, where *j* is *j* th modulation period.

SELECTION OF PRESSURE TRANSMITTER

The electronic pressure transmitter having accuracy of the order of 0.075% and good response characteristics were chosen for transmission of pressure signal. As the scan rate will be much higher than the transmitter response, the transmitter response will not effect the overall response drastically. Of course the noise filters provided in the transmitter circuitry may have marginal effect on the response. In the present set up , the contribution primarily due to valve positioner and valve friction provided for a dead band of 2% in overall response.

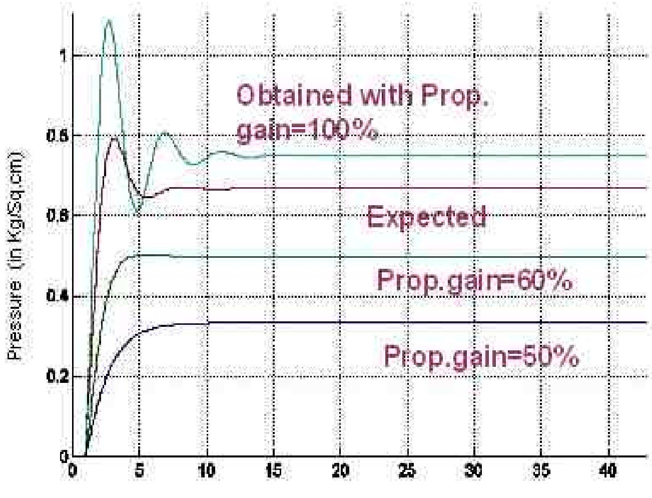
DATA ACQUISITION SYSTEM

As the pressure transient signal is of duration 4-5 seconds the recorder having a sampling rate of 125 msec was chosen so that 8 samples/sec can be recorded. For ease of analysis, the recorder stores the data in its internal memory of 32 MB and can be retrieved in CSV format for off line analysis.

PERFORMANCE EVALUATION

The performance characteristics obtained by use of proportional control with expected results were shown in fig.9 below.

The effectiveness of instrumentation and controls for studies on passive containment isolation was established. The introduction of PWM based valve positioner has improved the speed of the response with slight penalty of overshoot. The transient pressure signal requirement is met but the dead time due to the frictional effects is of the order of 5-10%. The controller gain was slightly reduced to keep overshoot within limits. The rise time of the pressure transient is of 180 msec.



Time (in seconds)

Fig.9 Performance characteristics using Proportional Control

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To obtain optimal process tuning and speed of response, the positioner is installed near to the diaphragm valve, integral action introduced and PWM based valve positioner characteristics improved.

CONCLUSIONS

The purpose of Containment Isolation was satisfactorily achieved by introduction of Passive safety mechanism. The Ventilation duct shaping in the form of U-shape facilitated for creation of necessary differential to isolate the containment from atmosphere. Also the effectiveness of instrumentation components in simulation of transient as in LOCA conditions was established. The design of instrumentation and the safety mechanism is thus validated. It is therefore safely conclude that the innovative safety pressure seal mechanism in ventilation system will serve its ultimate purpose and can be implemented.

NOMENCLATURE

C_V	Discharge coefficient of Control valve
KPa	Unit of Pressure
T	Period
d_{min}	Minimum value of Duty cycle
T_{vr}	Valve Response time
T_{pwm}	Pulse width modulation period
V	Voltage signal
U_p	PWM Signal
t	time
j	instance of time

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