SIMULATION OF RELIEF VALVE DYNAMIC BEHAVIOUR

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ABSTRACT

Three heavy water spill incidents occurred at Wolsong-1, Pickering-A, and Bruce-A power plants in late 1994 and early 1995. In all incidents, the heavy water spills were caused by opening of the degasser/bleed condenser relief valves (RV). Detailed assessment of these incidents were carried out by the owners of the operating plants and by AECL. One of the key lessons learned from this assessments is that stable operation of the RVs is required to prevent damage to valve internals and associated piping resulting from waterhammer/dynamic loads due to the RV chatter.

The RV chatter phenomenon depends strongly on the performance characteristics of the valve, the associated piping configuration, and the operating conditions. To help understand and explain the chatter phenomenon, and to assist the evaluation of the dynamic behaviour of the existing or new RV installations, two RV models were developed and incorporated into the existing waterhammer computer code, PTRAN. This paper describes the basic principle of the models and presents the simulation results in comparison with the test data.

1. Introduction

Three heavy water spill incidents occurred at Wolsong-1, Pickering-A, and Bruce-A power plants in late 1994 and early 1995. All incidents started out with a liquid relief valve (LRV) in the heat transport system (HTS) failing open and caused heavy water spillage as a result of the degasser/bleed condenser relief valves (RV) opening. Unstable operation (i.e., chattering) of the RVs resulted in damage to valve internals and, in the Pickering event, it caused a valve inlet pipe to fail. Although at no time were the plant workers or the public at risk and there was no abnormal release of radioactive materials to the environment, there were economic consequences from the incidents due to heavy water spills and reactor shutdown.

Detailed assessment of these incidents were carried out by the owners of the operating plants and by AECL (Reference 1, 2, and 3), and improvements were recommended to mitigate the consequences of LRV failure. One of the key lessons learned from this assessment is that stable (chatter free) operation of the RVs is essential to prevent damage to valve internals and associated piping from resulting waterhammer/dynamic loads.

Various options were considered to improve the performance of the degasser condenser RVs for the CANDU6 plants, such as refurbishing the existing RVs or replacing them with new RVs with appropriate design features to ensure chatter-free operation. After detailed discussions with various valve manufacturers and assessment of the performance characteristics of their products, a RV with vibration damper and proportional characteristics was selected to be the most suitable for CANDU6 units. The function of the damper device is to increase hysteresis and dampen the cyclic operation of the valve stem. This enables the valve to follow the system transient and eliminates chattering. The vibration damper (VBD) device replaces the usual upper spring retaining plate of the valve. The VBD consists of an internally loaded friction element which does not affect the normal operation of the valve but creates greater stem friction in the closing direction if the valve tries to cycle rapidly. Figure 1 shows the design of a Bopp and Reuther (B&R) RV.

To help understand and explain the chatter phenomenon, and to assist the evaluation of the dynamic behaviour of the existing or new RV installations, two analytical models were developed and incorporated into the existing waterhammer computer code, PTRAN. This paper describes the general dynamic behaviour of RV operation and the basic principle of the computer models. Simulation results are presented and compared with actual RV test data.

2. Relief Valve Dynamic Behaviour

Pressure relief valves are the most commonly used devices for overpressure protection of a pressure vessel, a component/equipment (e.g., heat exchanger) or a process system. The basic design principle of a pressure relief valve is based on the inlet pressure on the valve disc overcoming the counter loads exerted by the RV internals (i.e., spring force, friction force, and other auxiliary forces), allowing the valve to open and relieve a defined capacity.

When the pressure on the valve disc is low, the spring force exceeds the pressure force, and the RV remains closed. The RV starts to open when the pressure force surpasses the loads exerted by the RV. The speed of the RV opening depends not only on the pressurization rate, but more importantly on the specific design of the valve internals (i.e., spring, huddling chamber, and vibration damper device, etc.). Figure 2 shows the conventional type of spring-loaded relief valves used in the original design of the degasser/bleed condenser RVs in all CANDU plants. It is designed to open as quickly as possible once the inlet pressure passes the set pressure. This pop-open characteristic can be achieved by careful design of the valve geometry, in particular the huddling chamber, which allows the fluid to act over a larger valve disc area as the valve opens.

Due to the specific design of the valve internals, the RV generally starts to re-close at a pressure lower than the opening pressure. The reseat pressure depends mainly on the design of the valve geometry, particularly on the huddling chamber and the adjusting ring. Figure 3 shows the typical valve characteristics of a conventional pop-open RV.

As mentioned above, the RV dynamic behaviour depend strongly on the performance characteristics of the valve, the associated piping configuration, and the operating conditions. When the pressure upstream of the RV passes the set pressure, the RV opens initiating a flow in the relief line, which causes a pressure drop. The magnitude of this pressure drop depends on the piping configuration (i.e., length, diameter and number of fittings), the RV characteristics (i.e., pop-open/close or proportional), and the system transient (i.e., the pressurization rate). When the RV opens, the fluid immediately upstream of the RV is accelerated very quickly and the pressure at this location decreases rapidly, as shown in Figure 4. If the pressure drops below the reseat pressure, the RV will start to close. This may happen even though the system/vessel pressure is still above the RV set pressure. The same effect is expected for the reverse process. When the RV closes, the flow is decelerated resulting in a rapid rise in the RV inlet pressure. The upstream pressure may then exceed the relief setpoint causing the RV to change direction and re-open. In addition, pressure wave dynamic interactions will create pressure pulses below and above the RV set pressure. A fast-acting valve is likely to produce large pressure oscillations allowing the valve to fully close each cycle, causing chattering. This phenomenon will continue until the source of overpressurization is terminated.

The key parameters that affect the onset of valve chatter are discussed below.

a) Relief Capacity

The larger the relief capacity the more severe the pressure transient. Excess relief capacity may result in an unacceptable large pressure drop, causing the RVs to chatter.

b) Blowdown

Blowdown is the difference between the set pressure and reseat pressure of the RV. Increasing blowdown (i.e., lowering the reseat pressure) increases the margin between the first initial pressure dip and the reseat pressure. This allows the pressure immediately upstream of the RV to recover before chatter can occur.

c) Pop-Open/Close and Proportional Valve Characteristics

The rate of change of flow as a function of the valve motion can affect the pressure variation in the upstream pipe. The faster the valve opens/closes, the more fluid immediately upstream of the valve is accelerated/decelerated and this strongly affects the likelihood of chattering. Based on the discussions with valve suppliers and the recent Wyle Lab test results of the Pickering RVs, the design of the RVs originally used in the CANDU plants has a pop-open characteristic. The RV design close just as quickly when the reseat pressure is reached. The typical open/close time of these RVs is in the range of 20 to 100 ms.

On the other hand, a RV with proportional characteristics opens proportionally against the pressure, and its opening and closing speeds depend on the system pressurization rate. At the maximum pressurization rate under the most severe postulated overpressure transient in a typical CANDU plant, the proportional RV opening and closing speeds are expected to be much slower than the pop-open RV. This smooth pressure transient results in stable operation of the RV.

d) Valve Internal Design

Most of the original designs of the RVs used in CANDU plants have steam trim design for the valve disc and have pop-open/close characteristics. Discussions with valve suppliers concluded that the steam trim design for the valve disc is not suitable for liquid application as in the CANDU plants. The steam trim design tends to result in less stable operation under liquid conditions. They recommend a liquid trim design as being more suitable for the CANDU application.

e) Piping Configuration

The piping configuration (i.e., length, size, and number of fittings, etc.) is one of the most important parameters affecting the valve chatter behaviour. The longer the inlet line and/or smaller the pipe diameter, the larger the expected pressure drop and inertia effect which increases the likelihood of valve chatter. The small pressure drop due to a large size of inlet line and small number of fittings will also reduce the likelihood of valve chatter. Similarly, high back pressure caused by long, small diameter outlet lines contributes to chattering by increasing the closing force on the disc after the valve opens.

f) System Transient and Capacitance

The RVs respond to the system transient. When the system pressure rises above the set pressure, the RVs open to relieve the pressure from the system. If the system pressurization rate is very small due to low injection flow to the HT system and if the system capacitance is small (i.e., at low temperature condition), the system overpressure will be turned around very quickly by the RV operation and this may result in cycling/chattering of valves with pop-open characteristics. However, RVs with proportional characteristics and suitable opening/closing hysteresis would remain open to balance the small inflows to the HT system with no cycling /chattering.

3. Computer Code

3.1 PTRAN

The computer code PTRAN was used for the present study. PTRAN was developed for waterhammer analyses and is able to predict fluid flow and pressure transients in simple and complex piping systems. It has been used to simulate and analyze high pressure accumulators, high/low pressure emergency core cooling, liquid injection shutdown systems, feedwater system and many other hydraulic systems.

PTRAN is a one-dimensional single-phase fluid code which solves the continuity and momentum equations based on the method of characteristics (Reference 4). It has been validated against various commissioning test results (References 4) and experimental data (Reference 5). In all cases the PTRAN predictions show excellent agreement with the test results.

3.2 Valve Models

There was no relief valve model in the original version of PTRAN. Two RV models were developed and incorporated into PTRAN to simulate the dynamic behaviour of RV operations.

3.2.1 Valve Model 1

Valve Model 1 is a very simple model and it does not model the mechanical operation of the spring loaded relief valve. It simply models the RV performance characteristics (i.e., opening/closing speed, relief pressure, and reseat pressure) through the input data. It was assumed that the RV starts to open when the pressure upstream of the RV reaches the set pressure and continues to open until the pressure upstream of the valve drops below the reseat pressure where upon the valve starts to close. The RV continues to close until it is fully closed or until the local pressure rises above the set point, where the valve will start to re-open. Provided the pressure is above the set pressure or below the reseat pressure, the valve will continue to open/close at a predefined rate. The speeds of RV opening and closing are assumed to be independent of the local pressure. This assumption is considered to be acceptable for the pop-open/close type of RVs.

The valve discharge coefficient was adjusted to give the correct relief flowrate for the rated conditions.

3.2.2 Valve Model 2

As described in Section 3.2.1, valve Model 1 does not account for the momentum of the valve stem, the fluid forces applied onto the valve disc, and the forces exerted by the valve (i.e., spring force, friction, and vibration damper force etc.). A second valve model was therefore developed to account for these effects based on the equation of motion. The basic principle of the model is a force balance on the relief valve's moving parts as illustrated in Figure 1

4. Validation of RV Model 1

4.1 RV Testing

A series of tests were conducted at Wyle Laboratories in early 1995 to test the performance of the Pickering Unit-2 bleed condenser relief valves. The two valves were tested individually under different operating conditions. Figure 5 shows a schematic of the test rig. The tank was pressurized with nitrogen to achieve the required lift pressure and overpressure. The valves were typical spring-loaded relief valves. They had pop-open characteristics with an opening time in the range of 20 to 100 ms.

4.2 Comparison of Predictions and Test Results

Valve Model 1 was tested against the Pickering Wyle test data. Figure 6 shows the model of the test rig. Three runs were performed to simulate the Wyle tests at 30 °C, 150 °C and 250 °C. The RV characteristics (i.e., set pressure, reseat pressure, speeds of opening and closing) used in the simulation were derived from the experimental data. Figure 7 and Figure 8 show the comparison of experimental and simulation results of the pressure at the valve inlet for 30 and 250 °C respectively. The simulations showed good agreement with experimental data for all cases. The predicted initial pressure dip following the opening of the RV and the pressure spike resulted from closing of the RV agree very well with the experimental data. As discussed in Section 2, the initial pressure dip and the pressure spike are the two key parameters in determination of onset of the chatter operation. The good agreement of these parameters indicate that this simple valve Model 1 can be used to study the dynamic behaviour of a pop-open/close type of RVs and to evaluate the design adequacy of their installations from chatter-free operation viewpoint. However, it should be noted that this simple model may not be able to predict the cycling frequencies and the magnitude of pressure oscillations once chattering occurs due to the simplicity of the assumptions discussed in Section 2.

5. Validation of RV Model 2

5.1 B&R RV Testing

a) Testing at Bopp and Reuther Test Facility (B&R Tests)

A series of tests was carried out to demonstrate the proportional behaviour of the relief valves at the Bopp and Reuther test facility in Germany. The tests included the measurement of spring force and vibration damper force, the fluid force measurements, and the dynamic tests at different system pressurization rates. All tests were conducted at room temperatures.

Figure 9 shows a schematic of the test rig. The water tank was filled with water and pressurized with air. The system pressurization and depressurization rates can be controlled by manipulating the air regulating valve and the vent valve. The RV was mounted onto the end of the 8" diameter discharge pipe from the water tank. The test rig was fully instrumented, and connected to the data acquisition system, for instantaneous recording of the RV stem lift, the tank pressure and the pressure just upstream of the RV. The flows were measured by a calibrated orifice upstream of the RV. All data sampling was at sampling rates of 4800 per second to a maximum of 9600 per second and averaged to about 75 samples per second. A test run with a faster averaged sampling rate of 600 samples per second was conducted to confirm the acceptability of the 75 samples per second rate.

b) Test of B&R RV at Wyle Laboratory (Wyle Tests)

In May 1996, a series of tests was conducted at Wyle Laboratory in Huntsville, Alabama, USA. The common inlet line was about 22' long, as shown in Figure 10. The tests simulated the piping configuration of the CANDU 6 installation as closely as practical, including the two relief valves in parallel. Tests were conducted at three temperatures (21°C, 180°C, and 268°C) with various pressurization rates.

Figure 10 shows a schematic of the test rig. The test rig consisted of two water tanks (one acting as a buffer tank), a recirculating pump, a heater, an orifice-type flowmeter, nitrogen cylinders, steam supply, and associated piping. Nitrogen cylinders were used to pressurize the water tank and the rates were controlled by the pressure regulating valve and the vent valve. The water was heated by the heater and the steam supply. The "Megadac" high speed multi-channel data acquisition system was used, with 1000 Hz recording frequency for pressure, flow, lift, temperature and level measurements.

5.2 Comparison of Predictions and Test Results

Valve Model 2 was tested against the results of the B&R and Wyle tests, and the results are discussed below.

a) Comparison with B&R Tests

The PTRAN model of the B&R test rig is shown in Figure 11. The spring force, the vibration damper force and the fluid force were derived from the test results, and were input into the PTRAN code. Five test cases were simulated to cover the range of pressurization rates. The simulation results agree very well with the test results for all cases. Two cases (one for low pressurization rate and one for high pressurization rate) are presented here for discussion.

Figure 13a-d show the PTRAN simulation results in solid line for the low pressurization case. The test results are shown in dotted lines. As shown in Figure 13a, the system was initially pressurized at a low rate and was then reduced slightly immediately after opening of the RV. The system pressure was then further increased and held constant for a few seconds before depressurization. It can be seen from Figures a-d that the predicted transient pressure, lift, and flow agree very well with the experimental data. This confirmed that the valve Model 2 is able to capture all the dynamic behaviours observed in the testing.

Figure 14a-d show the PTRAN simulation results in solid line for the high pressurization case. The test results are shown in dotted lines. As shown in Figure 14a, the system was initially pressurized at a high rate and continued to pressurize to a pressure somewhat above the 110% relief set pressure before depressurization. As in Case 1, the predicted transient pressure, lift, and flow are in excellent agreement with the experimental data. This result again shows that valve Model 2 predicts very well the dynamic behaviours of a proportional RV with a vibration damper device.

b) Comparison with Wyle Tests

A number of PTRAN runs were performed to simulate the Wyle test cases using the same valve model (valve Model 2) developed based on the B&R testing. The PTRAN model of the Wyle test rig is shown in Figure 12.

The simulation cases cover all temperatures and pressurization rates tested at Wyle Laboratory. Similar to the B&R cold test simulation results discussed in a), the PTRAN predictions agree very well with the test data. Similar agreements were also obtained for all hot test cases (i.e. 180°C and 268°C). The simulation results of a typical hot test at 268°C are presented and discussed below.

The PTRAN simulation results are shown as solid lines in Figure 15. The test results are plotted in dotted lines in the corresponding figure. As can be seen from the figure, the predictions agree very well with experimental results for all parameters. At hot condition, the RVs open and close faster as compared to the cold case due to the extra force resulting from flashing. As a result, the initial pressure dip during opening and the pressure spike upon closing are somewhat larger than those for the cold case.

However, the magnitudes of these pressure dips and spikes are relatively small to ensure chatter-free operation. Valve Model 2 is able to capture the very fast-opening/closing and the proportional action of the valve as measured in the testing. These simulation results demonstrate that valve Model 2 can be used to study the dynamic behaviour of a proportional RV with vibration damper device and to evaluate the design adequacy of their installations from chatter-free operation viewpoint at the reactor operating conditions.

6. Conclusions

Two RV models have been developed to simulate the dynamic behaviours of spring-loaded relief valves. The two models were successfully tested against experimental results.

Valve Model 1 simply models the RV characteristics through the input data and does not model the mechanical operation of the valve. Despite the simplicity of the model, the simulation results show that this model predicts well the dynamic behaviours of a pop-open/close type of RV and can be used to evaluate the design adequacy of the RV installations from chatter-free operation viewpoint.

A more detailed model, valve model 2, was developed for a proportional type of RV with a vibration damper. The basic principle of this model is based on the force balance of the valve moving parts through the equation of motion. The effects of the mechanical operation of the RV on the RV dynamic behaviour are accounted for in this model. The excellent agreement of the simulation and test results demonstrates the capabilities of the model with the PTRAN code used in the study of the dynamic behaviours of a proportional RV with vibration damper device and the evaluation of the design adequacy of their installations from chatter-free operation viewpoint at the reactor operating conditions.

7. Acknowledgment

Contribution of the Joint CANDU Industry Generic Team members especially Don Jones and the CANDU6 Bopp and Reuther Valve Test Team members especially Phil Kidston and John Papp is greatly acknowledge. Input and support from various other individuals from AECL, Ontario Hydro, Gentilly-2, Point Lepreau, Bopp and Reuther and Wyle Laboratory is also much appreciated

8. References

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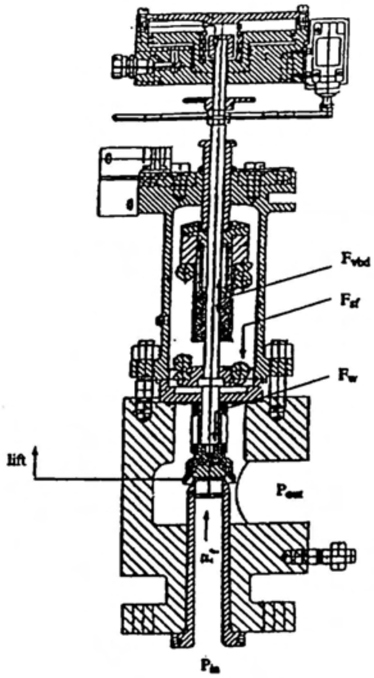


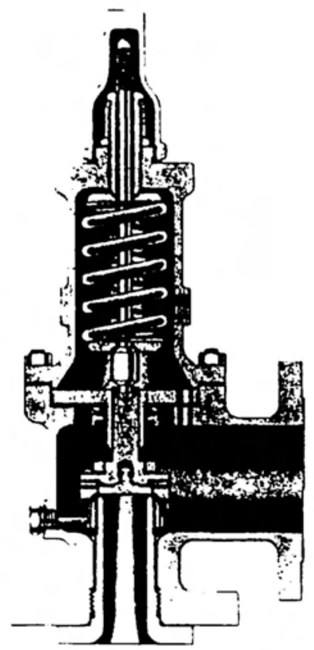
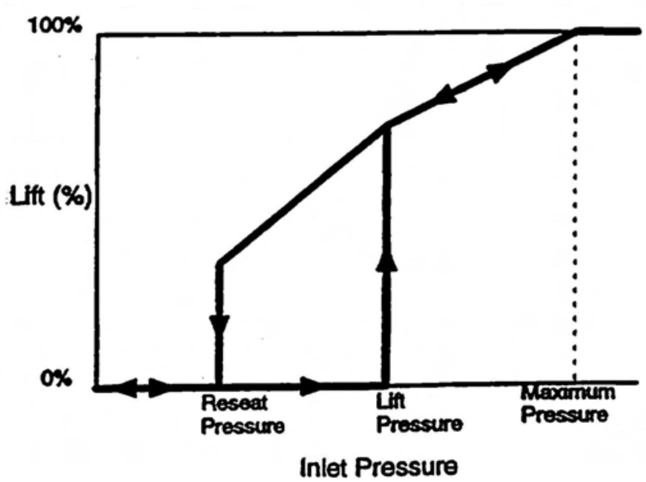


Figure 1 Proportional Relief Valve **Figure 2 Conventional Relief Valve**



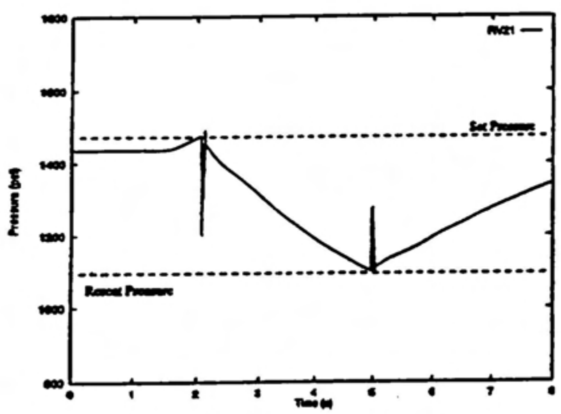


Figure 3 Typical Valve Characteristics of Conventional Relief Valve

Figure 4 Chattering Phenomenon

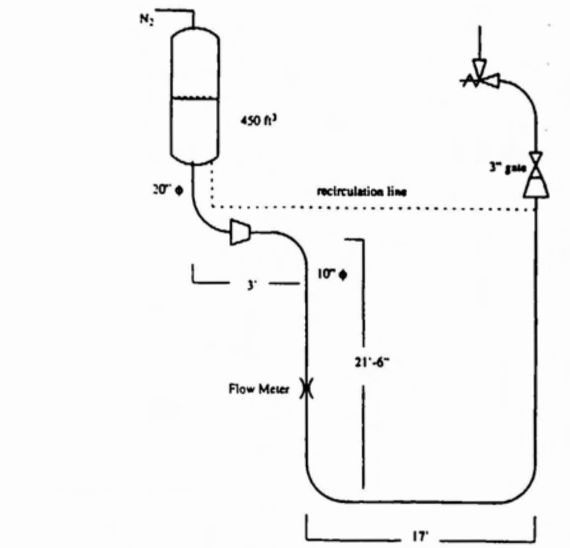


Figure 5 Wyle Test Rig (Pickering 2)

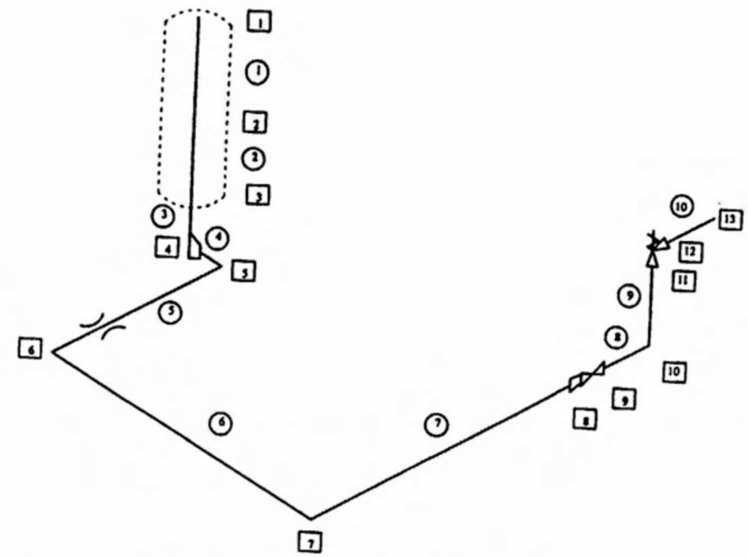


Figure 6 PTRAN Nodalization of Wyle Test Rig (Pickering 2)

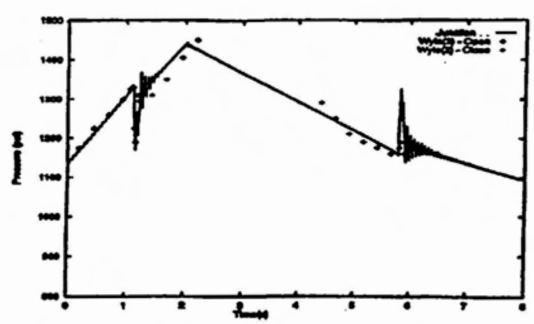


Figure 7 Wyle Test (Pickering 2) 30 °C

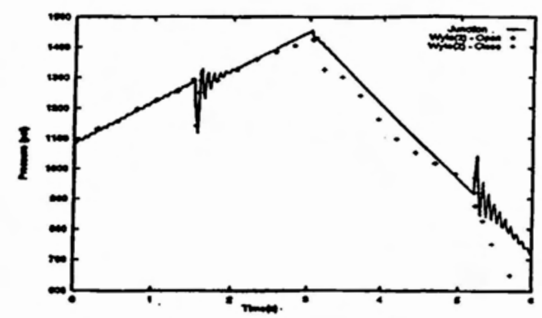


Figure 8 Wyle Test (Pickering 2) 250 °C

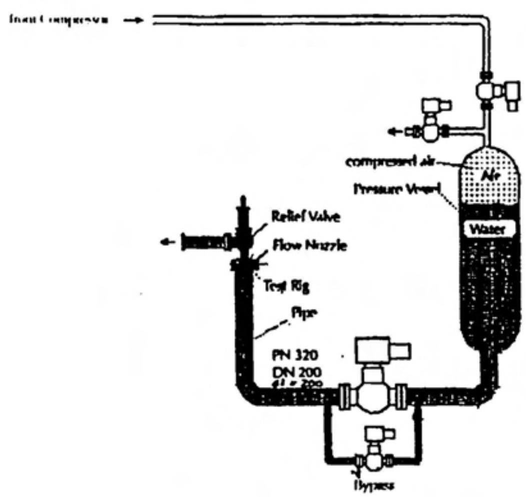


Figure 9 B&R Test Rig

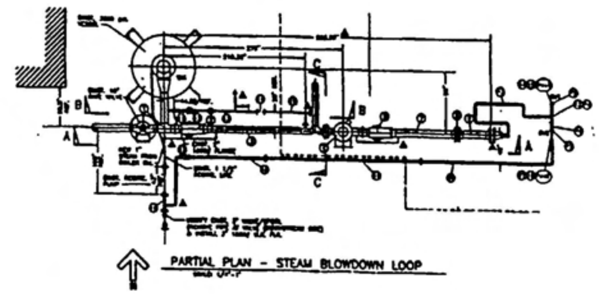


Figure 10 Wyle Test Rig (AECL)

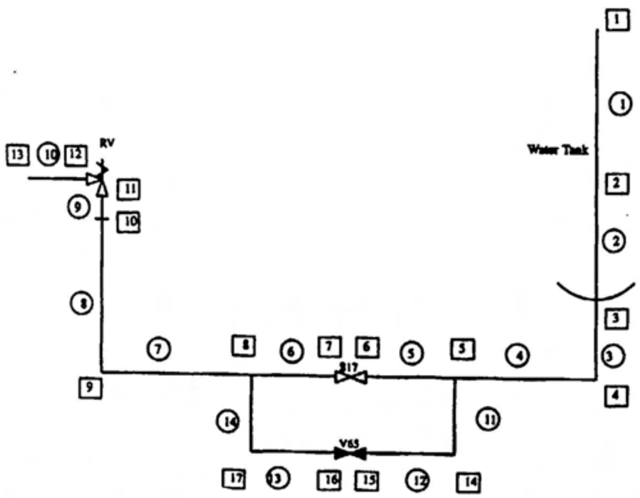


Figure 11 PTRAN Nodalization of B&R Test Rig

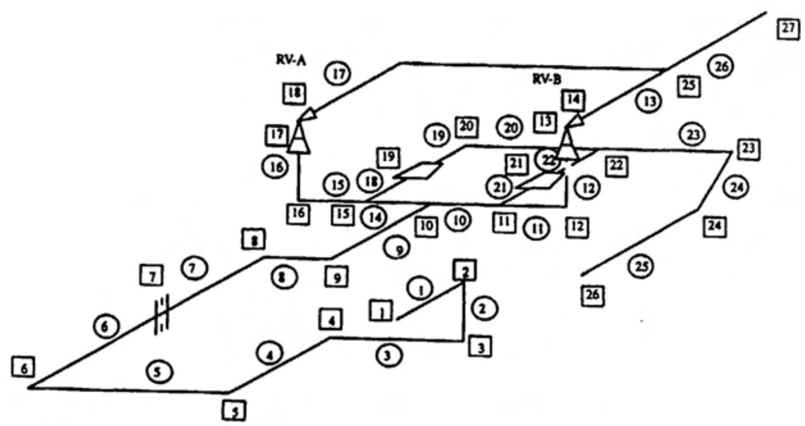


Figure 12 PTRAN Nodalization of Wyle Test Rig (AECL)

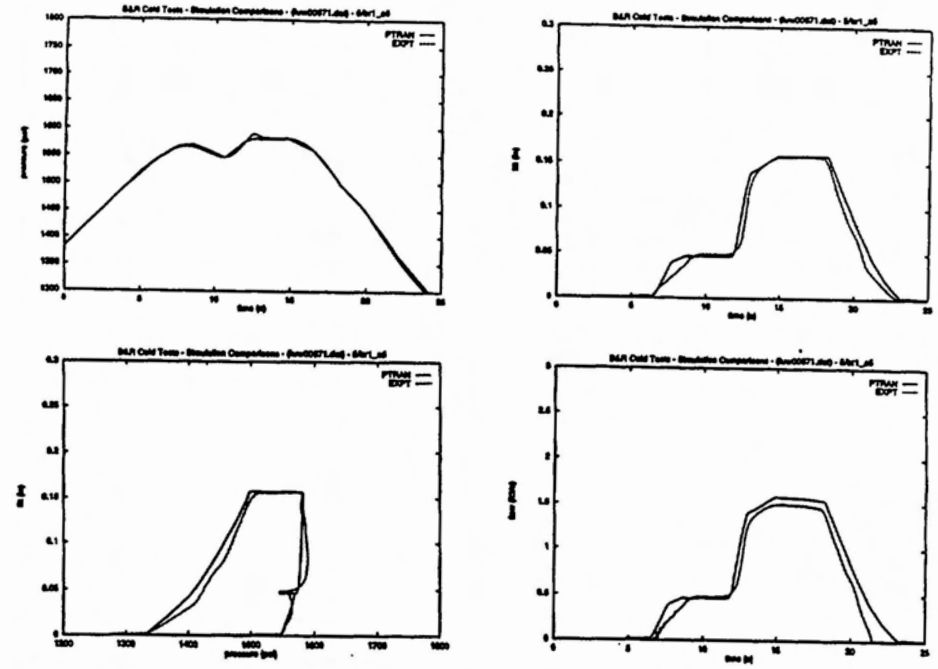


Figure 13 B&R Test - Case 1

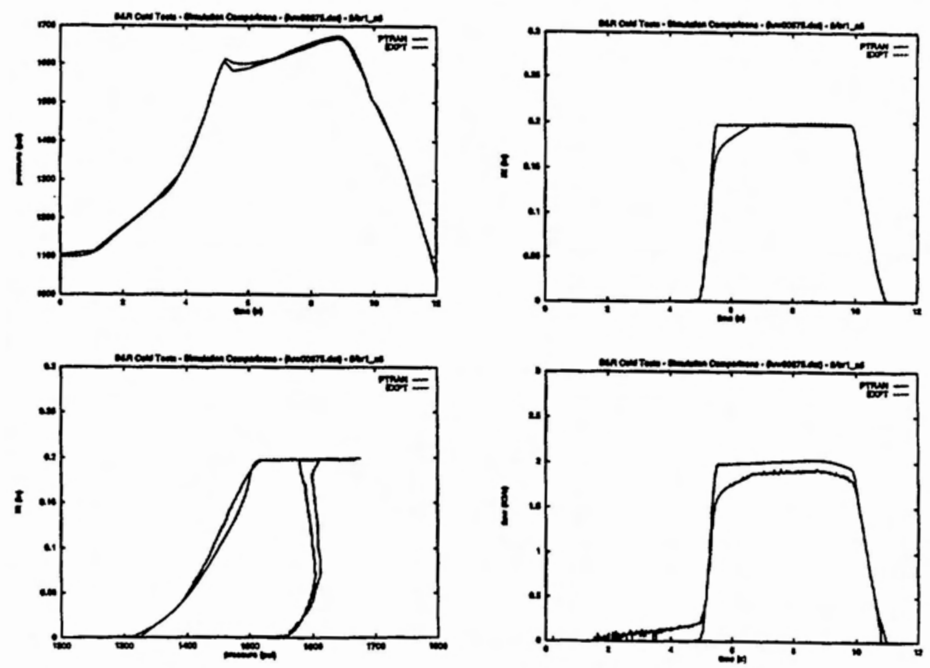


Figure 14 B&R Test - Case 2

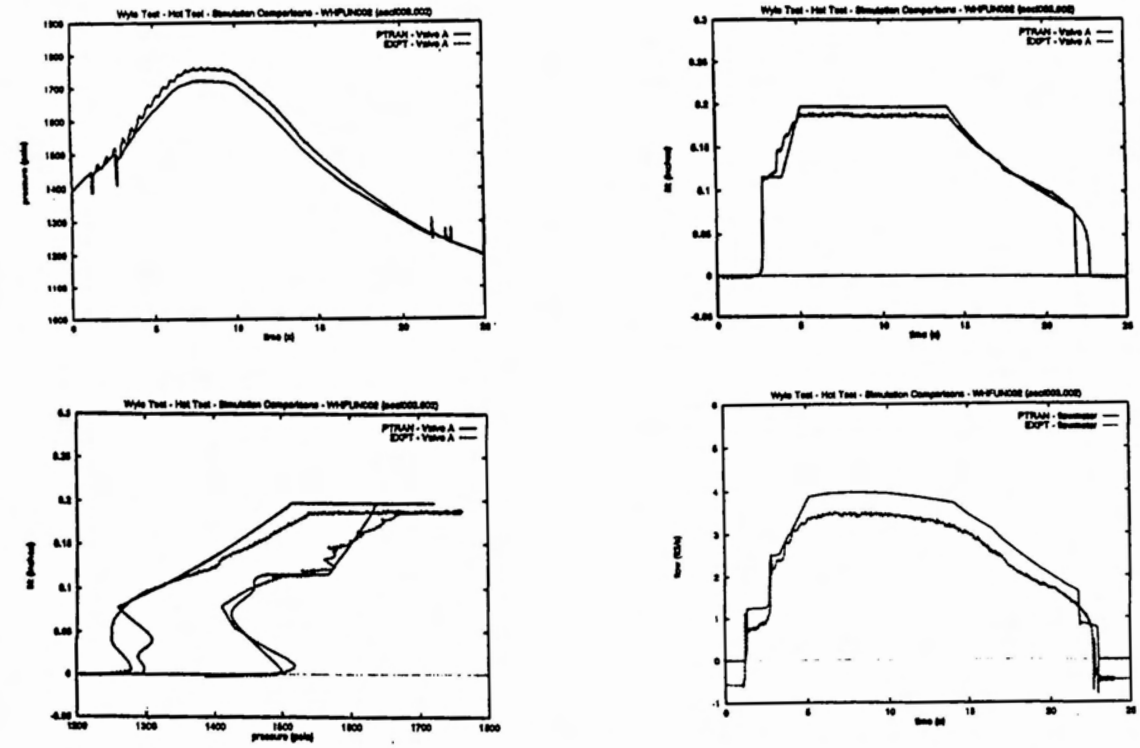


Figure 15 Wyle Test (AECL)