NONLINEAR TRANSIENT DYNAMIC RESPONSE OF PRESSURE RELIEF VALVES FOR A NEGATIVE CONTAINMENT SYSTEM

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A few nuclear power stations designed and built in Canada (e.g. Pickering Generating Station) utilize a multi-containment arrangement with a common vacuum building to provide a negative pressure containment envelope should a postulated accident occur in one of the containments. In the event that the pressure rises in one of the containments to a certain level, the pressure relief valves which are located in a vacuum duct joining the different containments to the vacuum building will open to relieve the pressure to the vacuum building where a spray system is actuated to condense the incoming steam. These safety related valves have a seismic Category 'B' according to Canadian Codes and Standards. Thus, they should remain intact and operational, and cause no loss of containment following a Design Basis Earthquake (DBE). These valves are approximately 6ft in diameter and consist of a housing in which a piston moves up and down. Two rolling neoprene diaphragms serve to prevent leakage and act as guides to reduce friction around the piston during vertical movements. The large size of these valves precludes any possibility for a full scale shaking test. In this paper the basis of the seismic qualification of these valves by a nonlinear transient dynamic analysis is presented. The nonlinear analyses conducted take into consideration the true nature of the behaviour of the piston during opening and accounts for piston rocking and sway effects, diaphragms folding, eccentricity of the center of mass and center of rigidity as well as the nonlinearities generated by gaps and friction in the system among others. The nonlinear analysis utilizes an explicit marching scheme to integrate the coupled equations of motion in the time domain. The response of the piston for the postulated simultaneous effect of pressure and an earthquake is obtained for different parameters and accident conditions. Response quantities such as accelerations, displacements, rotations, diaphragm forces as well as opening time during a design basis earthquake are obtained. The results of the different analyses, as related to the functional operability of the valves, are evaluated and discussed.
1. Introduction

A few nuclear power stations designed and built in Canada (e.g. Pickering Generating Station) utilize a multi-containment arrangement with a common vacuum building to provide a negative pressure containment envelope should a postulated accident occur in one of the containments. In the event that the pressure rises in one of the containments to a certain level, the pressure relief valves (PRV) which are located in a vacuum duct joining the different containments to the vacuum building will open to relieve the pressure to the vacuum building where a spray system is actuated to condense the incoming steam. The negative pressure containment system consists of the Reactor Building, the pressure relief system and the Vacuum Building. The arrangement of the structures for the Pickering Generating Station is shown in Figure 1. The pressure relief system consists of the pressure relief louvers, the ductwork which interconnects the reactor buildings, and the vacuum building, and 12 pressure relief valves which isolate the atmosphere of the reactor building from that of the vacuum building during normal operating conditions. These safety related valves have a seismic Category 'B' according to Canadian Codes and Standards (1). Thus, they should remain intact and operational, and cause no loss of containment following a Design Basis Earthquake (DBE). These valves are approximately 6 ft in diameter and consist of a housing in which a piston moves up and down. Two rolling neoprene diaphragms serve to prevent leakage and act as guides to reduce friction around the piston during vertical movements. Fig. (2) shows the different components of the Pickering valves.

2. Objective of Investigation

The general objective of the investigation is to demonstrate that the pressure relief valves can remain intact and operational and cause no loss of containment during and after a Design Basis Earthquake (DBE). The large size of the valves somewhat precludes any possibility for a full scale shaking test. Thus, the basis for the seismic qualification as presented herein is a dynamic analysis followed by an investigation of any possible failure modes due to a seismic event.

Different analysis techniques have been utilized in the investigation to quantify the performance of the valves. These techniques included linear elastic analysis, nonlinear time-history analysis and complex frequency-domain analysis. Whenever any uncertainty existed in the dynamic properties to be used, a conservative choice of the parameters was made or the analysis was conducted for a range of these parameters. It is concluded from all these analyses as discussed later that the valves are capable of performing their intended function during and after a DBE event and thus are considered to be seismically qualified as a Category 'B' component. The rest of the paper covers the different aspects of the investigation and the analysis techniques used.

3. Seismic Design Input Motions

The pressure relief valves are located in a concrete relief duct. The duct is a bridge type structure, 25' high by 20' wide supported on columns about 78' above grade level. The ground motion which may occur at the site will be amplified by this structure. A dynamic analysis for the duct structures has been conducted first. The model used in this dynamic analysis is three-dimensional in nature and was subjected to three components of the design basis ground motion to be expected at the site. The resulting three components of motion (two horizontal components and a vertical component) were developed at the floor level where the valves are located. These motion components constitute the seismic input for which the
valves should be qualified. As an example Figures 3 and 4 display the nature of the resulting motion developed in the transverse direction of the duct.

4. **Elastic Linear Analysis**

   A detailed linear dynamic analysis model was first formulated for the whole valve assembly which include the top and the bottom housing, vent pipe, receptacle and its four supporting rods, and the piston as supported laterally by the diaphragms.

   The linear elastic analysis was conducted utilizing the SAP IV program (2). The main conclusions of the elastic analysis are:

   (a) All the components of the valve assembly are rigid. The frequencies calculated are close to 33Hz. Thus, very little amplification of motion is expected. The valve components will experience basically the floor acceleration in a DBE event.

   (b) The only component which shows some flexibility is the piston itself as supported by the diaphragms. The level of acceleration experienced by the piston depends on the diaphragm properties and the amount of gaps between the piston and the casing.

   (c) Because of the rigidity of the valve assembly, the input motion to the inertial reference frame in which the piston moves is basically the floor acceleration. Thus an evaluation for the impact forces and the response of the piston is required. The details of this evaluation are discussed later.

5. **Complex Frequency Domain Analysis**

   To obtain the response of the piston as supported by the diaphragms in the linear elastic model, described before, the complex frequency-domain solution was utilized as an alternative to the conventional time-domain solutions. The maximum response acceleration for the piston obtained in this analysis is 54.57 in/sec\(^2\) for a longitudinal floor acceleration of 44.24 in/sec\(^2\) (amplification factor of 1.23). This horizontal acceleration will generate a total force in the upper and the lower diaphragms of 437 lb. This horizontal force when applied to the top housing (weighs approximately 6450 lb) does not affect the integrity of the valve assembly and in the actual installation may be resisted by the natural friction available (the required coefficient of friction to resist this force is less than 7%).

6. **Nonlinear Dynamic Analysis of PRV**

   To achieve an understanding of the behaviour of the PRV piston under the simultaneous action of a pressure excursion and a DBE event, a nonlinear dynamic analysis model which accounts for impact and friction was formulated. It has been established before that all the components of the PRV are rigid in nature, and thus experience the duct floor accelerations. The PRV piston located inside the housing will vibrate horizontally impacting the housing through the diaphragms in the horizontal direction. The rolling diaphragms in the Pickering PRV are intended to have a 1/8" gap all around between the piston and the housing. In addition due to the fact that the piston is laterally supported somewhat at random in the circumferential direction by the rolling diaphragms, the effective gap size may be greater than the nominal intended gap of 1/8". Because of this uncertainty in the gap size, as well as the uncertainty in the actual lateral stiffness of the rolling diaphragms, the nonlinear analysis is conducted for two extreme cases. The first case, Case (I) has no gaps and the second Case (II) has relatively large gaps of 0.5 in. on each side.

   The actual behaviour of the piston should fall somewhere between these two extreme cases. Due to the fact that impact forces are generated in a DBE event, the opening of the valve may be delayed because of the corresponding friction forces which may be developed. The
The mathematical model used, the degrees of freedom, and the notations are shown in Figures 5 and 6. The analysis is based on the following assumptions:

(a) The piston can be treated as a rigid body.

(b) Pressure excursion is known beforehand and does not get affected either by the piston or its motion.

(c) The piston housing is rigid (established before by the linear elastic analysis).

The equations of motion for the piston vibrating in an inertial reference frame can be written as:

\[
\begin{bmatrix}
M \{\ddot{u}\} + C \{\dot{u}\} + \{F\} = -M \begin{bmatrix}
\ddot{u}_H \\
\ddot{u}_V \\
\ddot{u}_N
\end{bmatrix} + \begin{bmatrix}
p(t) \\
oo
\end{bmatrix} \cdot A
\end{bmatrix}
\]

(1)

where:

- \(M\) = Mass matrix
- \(C\) = Damping matrix
- \(F\) = Force vector
- \(\ddot{u}_H, \ddot{u}_V, \ddot{u}_N\) are the duct floor horizontal, vertical, and rocking accelerations respectively
- \(A\) = Effective area which is subjected to the incident pressure excursion
- \(p(t)\) = Effective applied pressure time-history (the resultant upward pressure after subtracting gravity effects)

\[
\begin{bmatrix}
M \\
C
\end{bmatrix} = \begin{bmatrix}
G & \bar{g} \\
\bar{g}^T & \bar{g}_o^T
\end{bmatrix}
\]

(2)

where:

- \(G\) = A matrix whose columns are the eigenvectors of the initial elastic system (normalized with respect to \(M\))
- \(\bar{g}\) = Percentage of critical damping in the \(i^{th}\) mode
- \(\omega_i\) = Circular frequency of the \(i^{th}\) mode
- \(\bar{g}_o\) = Diagonal matrix with elements \(2b_i^2\).

The previous set of coupled equations of motion are marched in the time domain and the time-history of any response quantity is obtained. The marching scheme utilizes the explicit impulse acceleration method (3,4) (known alternatively as the central difference method). The nonlinear analysis takes into consideration the sway and the rocking effects of the piston, the eccentricity of the center of mass and the center of rigidity, gaps, friction, among other effects. Table (1) gives the different response quantities of the PRV piston for the two extreme cases discussed before (with no gaps and with gaps of 0.5 in.). It is clear from the table that due to the impact phenomenon, the response accelerations, displacements, and forces are very high compared to a linear analysis or a system with no gaps. Most important, the accelerations experienced by the piston vibrating in an environment with a 0.5 in. gap are almost four times those of a system with no gaps. In addition, the forces which the rolling diaphragms experience are almost 8 times more because of impact. The maximum force generated on either the upper or lower diaphragms was found to be 1437 lb. This force although very high compared to what would be predicted by a linear elastic analysis should not constitute any engineering concern as far as the structural integrity of the valve assembly is concerned. Figures 7 and 8 show the nature of the diaphragm reactions for a system with gaps.
To obtain a quantitative assessment of the effects of these impact forces on generating frictional forces which may delay the opening of the valve, the model was subjected to the longitudinal motion until attainment of peak level (approx. 7.0 sec). A pressure which would cause a nett upward constant force of 2000 lb. was then applied and was maintained constant. This constant force would be equivalent to approximately 0.5psi. Since in the design concept a 0.65psi is needed to overcome the self weight of the piston, the total pressure differential applied is approximately 1.15psi. This pressure was considered to be the minimum pressure available to open the valve under a DBE event. The coefficient of friction was assumed to be 0.30 and a coefficient of restitution was assumed as 1.0. Both of the coefficients are believed to be very conservative. The results of the analysis indicated that the piston motion in the vertical direction affected the lateral response very little. The opening time for a travel distance of 42.0 in. under 1.15psi as determined by the analysis under a DBE event is 0.61 sec. The time the piston would normally take to travel 42.0 in. under a nett upward force of 2000 lb. is 0.57 sec. Thus the effect of the DBE event is a delay in opening of 0.04 sec. This delay in opening is very small and does not constitute any harmful consequences. This delay in opening time is equivalent to approximately 7% increase in the regular opening time. Since the opening time is relatively small, such a small increase is not important from the engineering point of view.

7. **Valve Performance in a DBE Event and Conclusions**

Based on the previous studies, the following can be concluded as far as the valve performance is concerned in a DBE event:

(a) The DBE accelerations generated in all the valve components apart from the piston are equal to the duct floor accelerations (approximately 0.12g horizontal and 0.12g vertical). The level of the accelerations does not cause any disruption of seals. A tilt-up of the valve housing will not occur and a loss of containment anywhere will not happen. The stresses generated under these accelerations, considering the rugged nature of the different components, are very small.

(b) The DBE event when combined with a pressure excursion causes some delay in opening. Using very conservative assumptions, (e.g. 1% damping, coefficient of restitution of unity, gap size of 0.5 in. on each side, coefficient of friction of 0.30 and a nett opening pressure of 0.5psi only); The delay in opening amounted to less than 10% of the regular opening time. Such a very small delay neither affects the concept of the negative containment system nor the results of the LOCA analysis already conducted.

(c) When considering the most unfavourable dynamic conditions for possible 'ratchet' effects (e.g. free gaps of 0.5 in. on each side and a spring constant available of 3000 lb/in. only for each diaphragm after impact); It was found that the piston does rock and does impact the housing. This rocking was not found to cause a pronounced delay in opening. This is primarily because of the vertical travel velocity did not change substantially because of the frictional forces. The maximum impact force at the level of a diaphragm, considering what are believed to be the most unfavourable conditions, was found to be 1437 lb. The maximum instantaneous total impact force on the housing was found to be 1606 lb. If no gap was assumed rather than the 0.5 in. gap on each side, this force drops to 437 lb. These instantaneous impact forces which change signs with a somewhat high frequency content, when applied to a rigid housing weighing approximately 6540 lb, do not endanger the structural integrity of the valve assembly.
The final overall conclusion is that the functional operability of the valve is not affected by a DBE event and the valves can be certified to be qualified as seismic Category 'B' components.

TABLE I

<table>
<thead>
<tr>
<th>Quantity of Interest*</th>
<th>System with No Gaps</th>
<th>System with Gaps (0.5&quot; Each Side)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Max. Input Horizontal Acc. (in/sec²)</td>
<td>44.24</td>
<td>44.14</td>
<td>1.0</td>
</tr>
<tr>
<td>2. Max. Response Horizontal Acc. (in/sec²)</td>
<td>54.47</td>
<td>200.49</td>
<td>3.67</td>
</tr>
<tr>
<td>3. Max. Response Rotational Acc. (Rad/sec²)</td>
<td>0.83</td>
<td>4.67</td>
<td>5.63</td>
</tr>
<tr>
<td>4. Max. Response Horizontal Disp. (in)</td>
<td>0.10</td>
<td>0.81</td>
<td>8.10</td>
</tr>
<tr>
<td>5. Max. Response Rotation (Rad)</td>
<td>0.0057</td>
<td>0.056</td>
<td>0.82</td>
</tr>
<tr>
<td>6. Max. Horizontal Force on Piston (lb)</td>
<td>437.</td>
<td>1606.</td>
<td>3.67</td>
</tr>
<tr>
<td>7. Max. Moment on Piston (in. lb)</td>
<td>4824.7</td>
<td>27296.</td>
<td>5.66</td>
</tr>
<tr>
<td>8. Max. Force in Lower Spring (lb)</td>
<td>417.3</td>
<td>1075.5</td>
<td>2.58</td>
</tr>
<tr>
<td>9. Max. Force in Upper Spring (lb)</td>
<td>185.6</td>
<td>1436.6</td>
<td>7.74</td>
</tr>
</tbody>
</table>

*Input Motion is the Duct Longitudinal Horizontal Motion with a duration of 30 sec.

Mass of Piston 'm' = 8.0 lb.in⁻¹ sec²
Moment of inertia 'I' = 5832 lb.in. sec²
\( h_1 \) = 16.0 in. (see Figure 5)
\( h_2 \) = 43.0 in.
\( k \) = 3000 lb/in
\( b_{cg} \) = 24 in.
\( \beta \) = 1%
Damping Type = Modal Damping (equation 2)

References


FIG. 5 SIGN CONVENTIONS UTILIZED IN THE ANALYSIS

FIG. 6 NONLINEAR DYNAMIC MODEL

FIG. 7 LOWER SPRING FORCE TIME-HISTORY (Gap = 0.5", β = 10°)

FIG. 8 UPPER SPRING FORCE TIME-HISTORY (Gap = 0.5", β = 10°)