# Evaluation of Dynamic Loads Due to Chugging for BWR Mark-II Containments

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ABSTRACT

The dynamic loads induced by chugging which is assumed to occur in the case of a loss of coolant accident of a boiling water reactor, have been evaluated for a representative Mark-II containment as an example. The loads have been evaluated based on the analysis code ACERON developed by the authors and on the seven vent full scale tests performed at Japan Atomic Energy Research Institute.

The reasonability of the assumptions and of the analytical model for ACERON have been confirmed for the evaluation of the dynamic loads due to chugging, by simulating the dynamic pressures observed in the full scale tests. After confirming the applicability of ACERON for the dynamic load evaluation, dynamic load evaluation methods have been examined based on ACERON and the seven vent full scale tests.

The dynamic loads due to chugging have also been evaluated as an example for a representative Mark-II containment in Japan, and the obtained containment response have been enough small to warrant the containment integrity in the case of LOCA.

## 1. Introduction

In the case of a postulated loss of coolant accident (LOCA) of a boiling water reactor (BWR), the steam released from the reactor vessel is injected into the pressure suppression pool through the vent pipes and condenses. In the assumed story of LOCA, chugging phenomenon may occur when steam flow rate through the vent pipes becomes lower than $30 \sim 35$ $kg/m^2s$.

Chugging phenomenon is caused by the unbalance between steam supply through the vent pipe and condensation rate at the vent pipe exit. Since chugging phenomenon produces relatively large amplitude pressure spikes in the water, many experimental and analytical investigations have been performed for this phenomenon. In order to clarify the phenomena, small scale experiments have been performed and the characteristics of the phenomena have been clarified.[1]∿[4] On the other hand, large scale tests have been performed[5],[6] for the purpose of the dynamic load evaluation caused by the dynamic phenomena including chugging. In the large scale tests, the Mark-II Containment response tests performed by Japan Atomic Energy Research Institute aimed at the investigation on the LOCA hydrodynamic loads in the BWR Mark-II containment systems. The tests, called JAERI CRT, were performed using 20° sector model containment with seven vent pipes. As reported,[7],[8] one of the most important factors that JAERI CRT clarified under the full scale multi-vent conditions is that the dominant frequency components of the dynamic pressure induced in the pool by chugging correspond to those expected to be caused by pressure wave propagation and reflexion in the vent system.

Since chugging phenomenon is caused by the unbalance between steam supply and condensation rate as mentioned, the dynamic pressure induced by chugging depends on the local thermal-hydraulic conditions where steam bubbles collapse. In a real BWR containment which has more than a hundred vent pipes, it is reasonable to expect that the thermalhydraulic conditions at the vent pipe exits differ from one vent pipe exit to another, resulting in random nature of chugging. JAERI CRT results showed the random nature of chugging. That is, chugging occured out of phase at each vent pipe and the magnitudes of dynamic pressures induced at vent pipe exits differed from one vent pipe to another.

The authors developed an analysis code ACERON in order to evaluate the dynamic loads caused by steam condensation based on 'full scale' test results, and proposed a dynamic load evaluation method[8] based on ACERON and on JAERI CRT results.

This paper describes the dynamic load evaluation based on ACERON and on JAERI CRT results. Since JAERI CRT was performed with seven vent pipes, multi-vent effects can be taken into account inherently by evaluating the dynamic loads based on JAERI CRT. Although enough data have been obtained from JAERI CRT for the dynamic load evaluation, the whole data have not been reported. Therefore, the dynamic loads have been evaluated conservatively based on the reported data.

## 2. Analysis of the Dynamic Pressure

Based on the observations in the large scale tests, the dynamic pressure induced by chugging has assumed as the resultant pressure caused by the pool-vent system responses to the hydrodynamic perturbations due to steam condensation at the vent pipe exits. By this assumption, chugging phenomenon can be devided in two portions from the view point of the dynamic load evaluation. One is the hydrodynamic perturbation generation process and the other is the excitation process of the pool-vent system responses. The former process is related with condensation phenomena at the vent pipe exits. Since the condensation phenomena are governed by the local thermalhydraulic conditions as pointed out, it seems to be difficult to determine the hydraulic perturbations in a deterministic way. However, the large scale test results show that the pool-vent system responses dominate the induced pressure in such a large system as a BWR containment. Therefore it seems unnecessary to determine the hydrodynamic perturbations precisely. The random nature of chugging caused by the uncertainty of the local thermalhydraulic conditions are taken into account for the dynamic load evaluation process. The latter process, the excitation process of the pool-vent system responses, is important since the responses dominate the induced pressure.

In the analysis code ACERON, the pool-vent system responses to the perturbations at the vent exits are analyzed. In the pool, the acoustic wave equation was assumed to govern the fluid flow. That is,

$$(\nabla^2 - \frac{1}{C_w^2}\frac{\partial^2}{\partial t^2})\, p(\vec{r},t) = f(\vec{r},\vec{r}_i,t) \tag{1}$$

$$\partial p/\partial n = 0 \;; \quad \text{at the pool boundary} \tag{2}$$

$$p = 0 \;; \quad \text{at the free surface} \tag{3}$$

were solved analytically for the arbitrary sector of a concentric cylinder, where $p(\vec{r},t)$ is the dynamic pressure, $f(\vec{r},\vec{r}_i,t)$ the contribution of bubble collapse or oscillation at $\vec{r} = \vec{r}_i$, $\nabla^2$ the Laplacian, $C_w$ the sonic velocity in water and n the normal at the boundary. Since the presence of small air bubbles which might be separated from water by temperature rise or which might come from the drywell, was considered to reduce the sonic velocity markedly, the compressibility of the fluid was taken into account as shown in eq. (1).

On the other hand, pressure waves in the vent pipe were assumed to be one-dimensional in space. The dynamic pressures in the vent pipes were solved by the method of characteristics, that is,

$$\pm C_s \frac{dp}{dt} + \rho_s \frac{dv}{dt} + \frac{\rho_s F}{2D}|v|v = 0, \quad \frac{dx}{dt} = \pm C_s \tag{4}$$

were solved numerically. Where $p = p(x,t)$ is the dynamic pressure, $v = v(x,t)$ the steam velocity, $C_s$ the sonic velocity in steam, $\rho_s$ the steam density. By using the method of characteristics, the influences of vacuum breaker actuations due to chugging on the dynamic pressure can be taken into account rather easily in the case that vacuum breakers are set on the vent pipes.

Eqs. (1) $\sim$ (3) and (4) were coupled by the hypothetical source at the vent pipe exits. The condition at the steam/water interface was given as

$$p(x,t)\big|_{x=0} = \frac{\rho_w}{4\pi R}\,\frac{dm(t)}{dt}\;, \tag{5}$$

where $\rho_w$ is the water density, m(t) the strength of the source and R the equivalent sphere assumed as steam/water interface. Eq. (5) means the continuity of the pressure through the interface.

In order to confirm the reasonability of the assumptions and of the analytical model for ACERON, the dynamic pressure observed in JAERI CRT was simulated. Figure 1 shows the analysis model for the JAERI CRT facility. The wetwell was modeled as 20° sector of a concentric cylinder whose inner and outer diameters were 4.74 m and 13.54 m, respectively. The drywell was treated as a lumped capacitance which has the same volume as that of the drywell. The source functions applied at the vent exits were defined to simulate the dynamic pressures observed at the vent pipe exits. However, the dynamic pressure had been measured only in five vent pipes of seven when the simulation was performed. Therefore, source functions for two vent pipes where the dynamic pressures had not been measured, were assumed to be same as those for the neighboring two vent pipes.

Figure 2 shows a simulation example for the dynamic pressure in a vent pipe. Three pressure time histories correspond to those at three different point in the vent pipe. Since the calculated pressure time histories show the features similar to those observed, the assumptions and analytical model are expected to be reasonable for the evaluation of the dynamic pressure in the vent pipes.

A simulation example for the dynamic pressure in the pool is shown in Figure 3. The calculated pressure time histories also show the features similar to those observed without some spikes of very high frequency in spite of the uncertainty in the source functions for two vent pipe exits. The calculated pressures were also examined in frequency domain by comparing the PSDs of the calculated pressures with those observed. The frequency components of the calculated pressures corresponded well to those observed. Therefore, the assumptions and analytical model for ACERON are also reasonable for the evaluation of the dynamic pressure in the pool which causes the dynamic loads.

## 3. On the Dynamic Load Evaluation Method

If all Mark-II containments have same dimensions as JAERI CRT containment including the water level in the pressure suppression pool, and if every LOCA condition has been simulated in JAERI CRT for each BWR Mark-II plant, the dynamic responses can be assessed for real containments without such an analysis code as shown here, by applying the dynamic loads observed in JAERI CRT directly to the real containments. However, the BWR Mark-II containment dimensions differ from one plant to another which causes differences in the frequency components of the induced pressure by chugging. Since the frequency components dominate the dynamic responses of the structures, it is important to take into account the differences in containment dimensions especially in vent pipe length which dominates the dominant frequency components of the dynamic pressure in the pool as shown in JAERI CRT results.[7]

Considering the structural responses to the dynamic loads and the random nature of chugging, it is reasonable to define the dynamic loads so as to satisfy the required conditions for the dynamic loads in frequency domain. One of the required conditions is to envelope the whole data obtained from JAERI CRT in frequency domain. This condition gives very conservative load evaluation. The required condition based on the statistical analyses of the obtained data gives more reasonable load evaluation[9]. The authors proposed the dynamic load evaluation methods.[8],[9] In the proposed methods, the design source functions were defined so as to produce the dynamic pressure whose PSD enveloped the design spectrum based on the data obtained from JAERI CRT.

## 4. Dynamic Load Evaluation Example for a Mark-II Containment

A typical design source function is shown in Figure 4. The source functions correspond to the hydrodynamic perturbations caused by steam condensation. The shape of the source function was decided based on the observations in small scale experiments, since the hydrodynamic perturbations were expected to be observed rather directly as the dynamic pressures in the small scale experiments because of the higher pool-vent system eigen frequencies which depended on the dimensions. The magnitude and time duration of the source function were decided to produce the dynamic pressure which satisfied the required condition. As a required condition for the dynamic loads, a design spectrum was defined[8] based on the data obtained from JAERI CRT Test 0002 which produced many severe chugs. The desing spectrum is shown in Figure 5 with the spectra produced by the design source. Since the deviations in the dominant frequencies of the dynamic pressure observed were expected to be caused by the deviations in the sonic velocity in steam, three different sonic velocities in steam, 285, 326 and 407 m/s were used in order to envelope the design spectrum reasonably.

Figure 6 shows an example of the evaluated dynamic pressure at the pool bottom of a representative Mark-II containment. The dynamic responses of the containment wall was obtained by applying the calculated dynamic pressure to the fluid-structure coupled model for the containment.

Figure 7 shows an example of the calculated stress under the symmetrical load condition which produces the severest stress for steel containments. This figure shows that the obtained stress is enough small to warrant the containment integrity.

As shown in JAERI CRT results[7], the dynamic pressure induced by condensation oscillation which is also one of the important phenomena in the case of LOCA, has similar features to that by chugging without the continuity of the pressure oscillation. The dynamic loads due to condensation oscillation can be evaluated in the same manner as for chugging by using ACERON. In the case of condensation oscillation, the hydrodynamic perturbations are enough frequent to produce continuous pressure oscillations.

Since the analysis code ACERON can analyze the dynamic pressures in the vent system as well as in the pool, the dynamic loads due to chugging or condensation oscillation can be evaluated for any Mark-II containment which has different dimensions from JAERI CRT facility.

## 5. Conclusion

The analytical model has been shown for the dynamic load evaluation due to chugging. Dynamic load evaluation methods and evaluation examples are also examined using the proposed analytical model. Obtained concluding remarks are as follows.

(1) The assumptions and the analytical model for the analysis code ACERON are reasonable since ACERON can well simulate the dynamic pressures in the pool as well as in the vent pipes observed in JAERI CRT.

(2) The evaluated stress of a representative Mark-II containment is enough small to warrant the containment integrity in spite that the dynamic load has been evaluated conservatively.

## References

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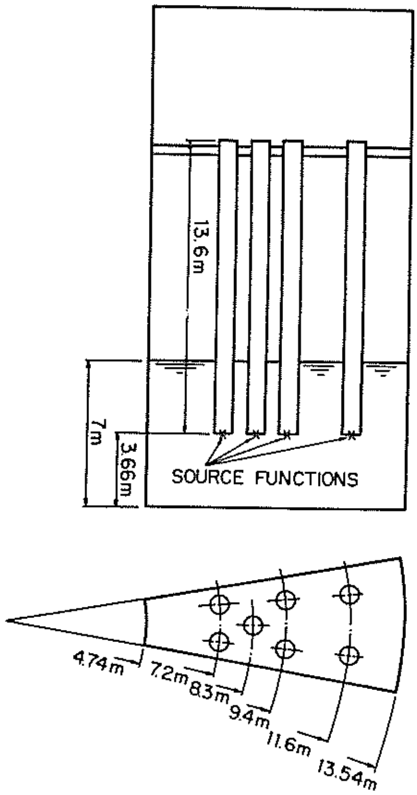


FIG. 1 Analysis Model for JAERI CRT Facility

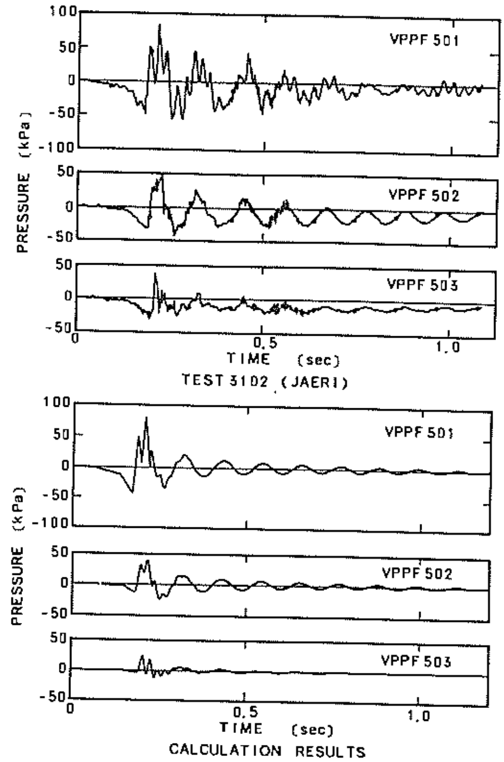


FIG. 2 Simulation Example for Dynamic Pressure in the Vent Pipe

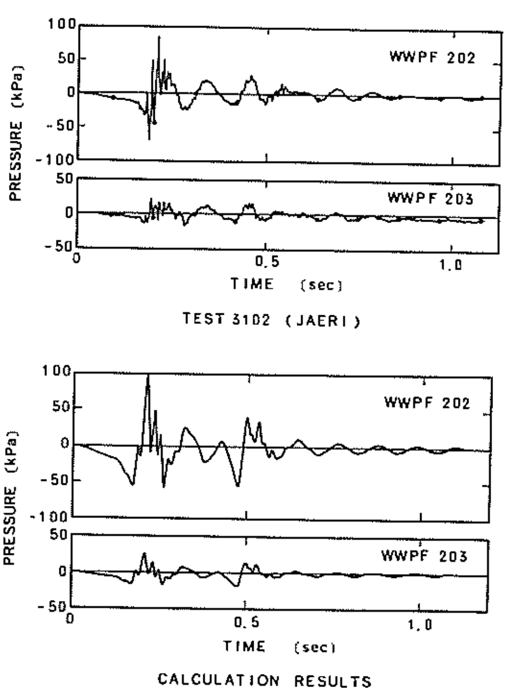


FIG. 3 Simulation Example for Dynamic Pressure in the Pool

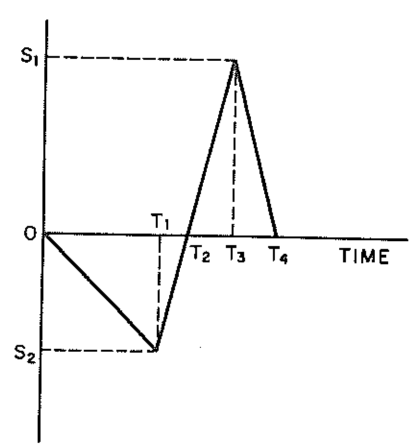


FIG. 4 Typical Source Function

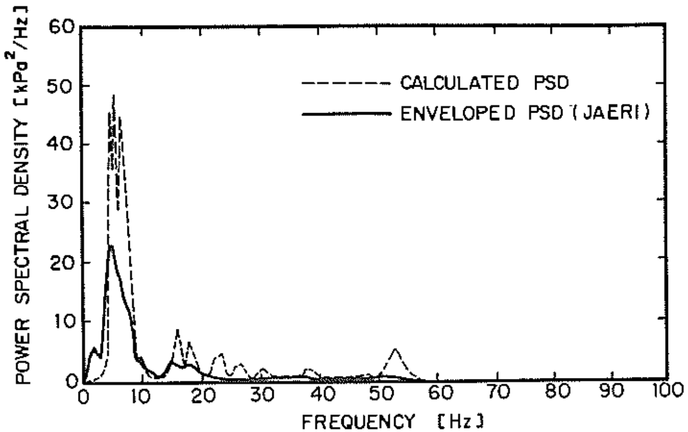


FIG. 5 Design Spectrum and Spectra Obtained by Design Source

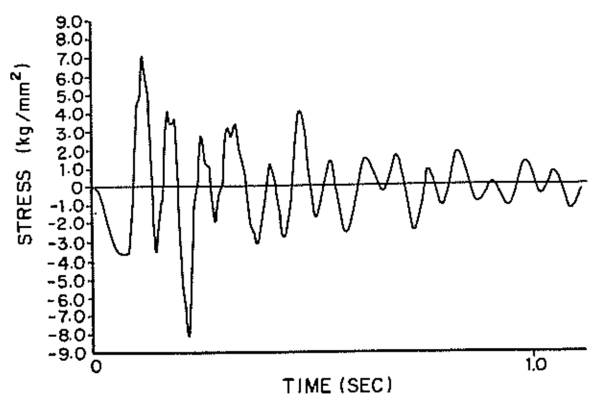


FIG. 7 Example of Containment Wall Response to the Evaluated Dynamic Load

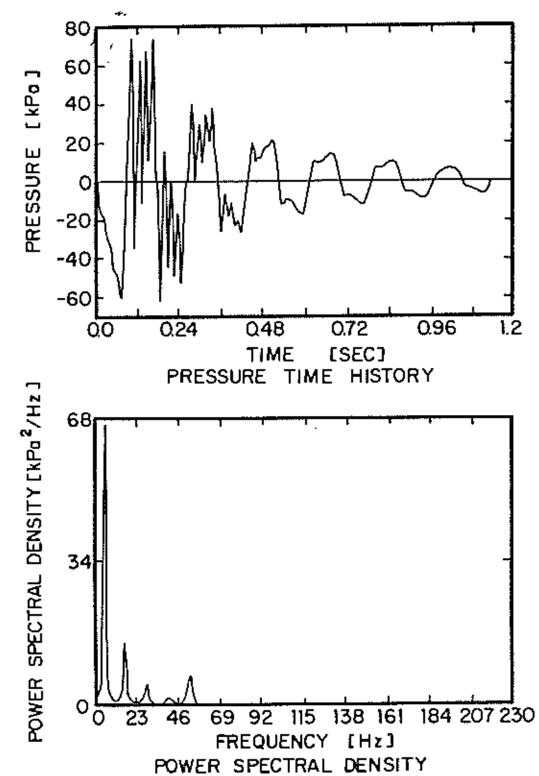


FIG. 6 Example of Evaluated Dynamic Load at the Pool Bottom