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Evaluation of Blast Wave Effects on Reactor Coolant System

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1. Introduction

When a high energy line pipe break (HELB) occurs, the reactor coolant system (RCS) is affected by several dynamic effects. The effects of jet impingement, thrust, subcompartment pressurization, nozzle loads, and blowdown load in the reactor internals (RI) are generally known [1] and have been evaluated so far.

In SRP 3.6.2 [2], U.S. Nuclear Regulatory Commission (NRC) concerns that blast wave formed prior to jet would cause significant load on surrounding structures, systems, and components (SSCs) in the event of high-pressure pipe break.

The RCS branch line pipe breaks (BLPB) are categorized as primary side breaks and secondary side breaks. Primary side breaks are the postulated breaks of the primary pipe lines which are not eliminated from the postulation of the breaks by application of the leak-before-break (LBB) principle. Secondary side breaks are the postulated breaks in the secondary system pipes which are branched from the steam generator (SG) such as the main steam line, feedwater lines, blowdown, and recirculation line [1]. The RCS BLPB analyses for APR1400 had been performed for the break cases considering the dynamic effects except blast wave due to the HELB. Reponses from the enveloped values of all break cases were used for the RCS design.

In this study, the blast wave effects on the RCS due to the main steam nozzle break for APR1400 are evaluated. The forces and moments and response spectra induced by blast wave loads at the RCS main components are included in this evaluation.

2. Methods and Results

2.1 Blast Wave

Blast wave due to a pipe break is a pressure propagating in the air from the break location. In the event of high energy line break, a blast wave propagates from both sides of the broken pipe. The blast wave expands spherically and hits the surface of SSCs. When a main steam nozzle of SG is broken, blast wave load in addition to thrust force and jet impingement are imposed on SG. Fig. 1 shows the a schematic of blast wave expansion in case of main steam nozzle break.

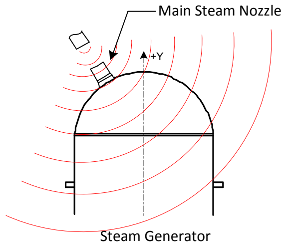

Fig. 1. A schematic of blast wave expansion in case of main steam nozzle break

Fig. 2 shows the typical blast wave's pressure time history. The pressure wave starts from ambient pressure and goes up to peak overpressure, and then goes down to ambient pressure. After the positive duration, the pressure goes down below ambient pressure referred as negative duration[3].

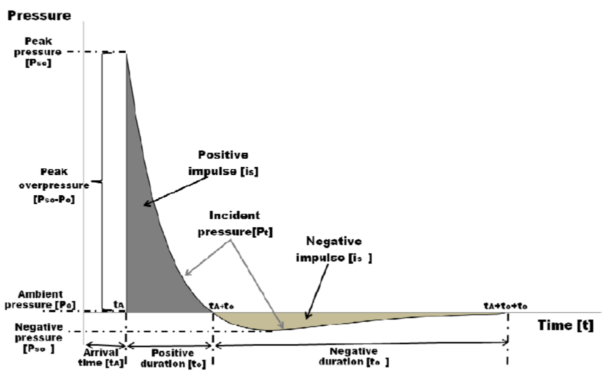

Fig. 2. Typical blast wave's pressure time history [3]

2.2 Analysis Model

RCS structural analysis model for evaluation of blast wave load is a lumped mass beam model as shown in Fig. 3. This model includes the reactor vessel, two SGs, four reactor coolant pumps, and reactor coolant piping. Gaps in RCS supports are modeled as gap element.

2.3 Branch Line Pipe Break Analysis

A nonlinear time history analysis has been performed using thrust force, jet impingement load, and blast wave load as input loads. The rise time of thrust force and jet impingement load is 0.001 second as required in SRP 3.6.2 [2]. The time profiles of thrust force and jet impingement are shown in Fig. 4.

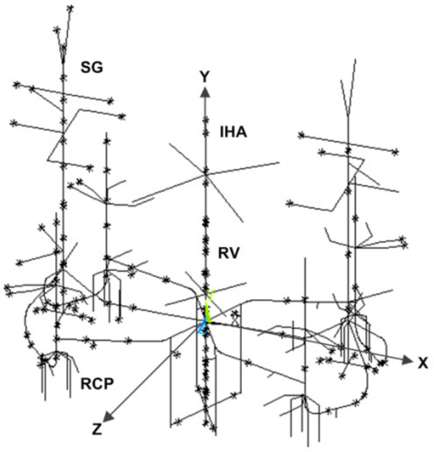

Fig. 3. RCS structural analysis model

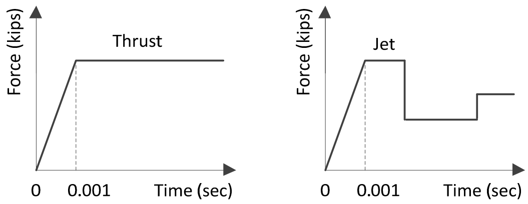

Fig. 4. Time profiles of thrust force and jet impingement load

Thrust force and jet impingement load are applied on the main steam nozzle as shown in Fig. 5.

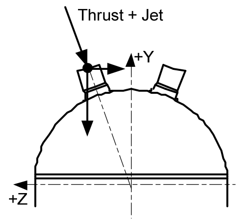

Fig. 5. Load application of thrust force and jet impingement load on main steam nozzle

Pressure time histories due to the blast wave are derived from computational fluid dynamics (CFD) analysis. Blast wave loads are calculated from the pressure time histories and surface area of the SG for each time step. The nodes where blast wave load are applied are shown in Fig. 6. The time histories of blast wave loads for three directions are shown in Fig. 7. Force time history in north-south direction looks different from the other vertical and east-west directions. This is because the blast wave is reflected by primary and secondary shield walls which are located in north-south direction of the SG. Even though blast wave is formed prior to jet formation, jet impingement load and blast wave load are applied to the SG at the same time conservatively.

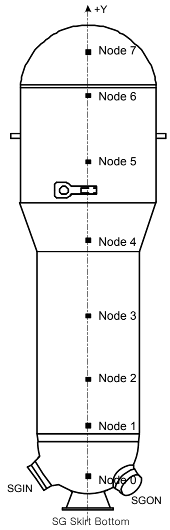

Fig. 6. Nodes for blast wave load application

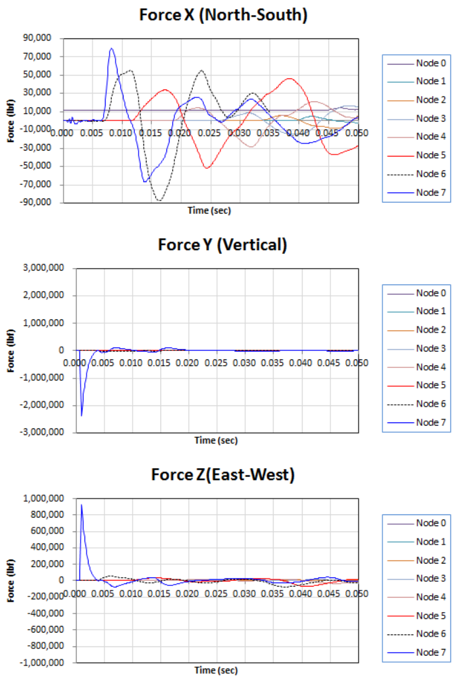

Fig. 7. Time histories of blast wave load

2.4 Analysis Results

From the results of the analysis, RCS support and nozzle loads were compared with those of the analysis without blast wave loads. Table I shows the comparison of support loads between the analysis with blast wave load (case 1) and without the blast wave load (case 2). It shows that there is the biggest increase in SG snubber load. RV column support loads are also increased up to about 30 percent. RCP support loads remain almost the same as those of case 2.

Table I: RCS support loads of main components

<table>
<tr><td rowspan="2">RV column</td><td>Fa</td><td>Fb</td><td>Fc</td><td>Ma</td><td>Mb</td><td>Mc</td></tr>
<tr><td>1.16</td><td>1.26</td><td>1.30</td><td>1.32</td><td>1.34</td><td>1.16</td></tr>
<tr><td rowspan="2">SG vertical</td><td colspan="4">Sliding Base</td><td colspan="2" rowspan="2"></td></tr>
<tr><td colspan="4">1.03</td></tr>
<tr><td rowspan="2">SG horizontal</td><td colspan="2">Upper Key</td><td colspan="2">Snubber</td><td colspan="2">Lower Key</td></tr>
<tr><td colspan="2">1.06</td><td colspan="2">3.02</td><td colspan="2">1.25</td></tr>
<tr><td rowspan="2">RCP</td><td colspan="2">Lower</td><td colspan="2">Upper</td><td colspan="2">Vertical</td></tr>
<tr><td colspan="2">1.00</td><td colspan="2">1.05</td><td colspan="2">0.79</td></tr>
</table>

Note:1. Ratio of support loads; case 1/case 2
2. F and M stands for force and moment, respectively.

RCS main components' nozzle loads of case 1 and case 2 are compared in Table II. Maximum increase is found in axial load (Fa) of RV outlet nozzle. From the above evaluation, it is found that support and nozzle loads in north-south directions are increased.

Table II: RCS nozzle loads of main components

Nozzle	Fa	Fb	Fc	Ma	Mb	Mc
RV inlet	1.22	0.87	1.19	1.08	1.05	0.83
RV outlet	2.30	1.21	1.02	1.00	0.95	1.10
SG inlet	1.41	0.97	2.22	0.99	1.39	0.99
SG outlet	1.26	1.23	1.07	1.04	1.08	1.30
RCP inlet	1.14	1.09	1.07	1.05	0.99	0.97
RCP outlet	1.18	0.84	1.34	1.17	1.39	0.87

Note:1. Ratio of nozzle loads; case 1/case 2
2. F and M stands for force and moment, respectively.

Although the RCS support and nozzle loads are increased, RCS design loads are not affected by these increases because the SG main steam nozzle break is not a governing break. One of the governing breaks is the SG feedwater nozzle break from which a blast wave is not formed.

SG response spectra for the main steam nozzle break case are also compared in Figs. 8 through 10. The response spectrum in north-south direction is increased for all frequency range while only high frequency region of the response spectra is increased in vertical and east-west directions. It can be reasonably expected from the shape of the force time histories in Fig. 7.

To evaluate the impact on the RCS design due to the response spectra of case 1, the enveloped response spectra for all break cases which contains response spectra from other break cases including feedwater nozzle break case were generated and compared. The response spectra in north-south direction of main steam nozzle break case is enveloped by those of other break cases as shown in Fig. 11. The high frequency region of the response spectra still higher than those of the other break cases in the vertical and east-west directions shown in Figs. 12 and 13, respectively. However, since the frequency region is higher than 100 Hz, it would not have an impact on the RCS main components' design.

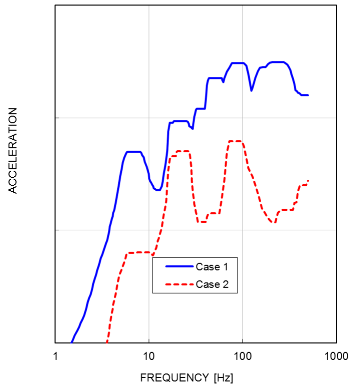

Fig. 8. SG response spectra: main steam nozzle break in North-South

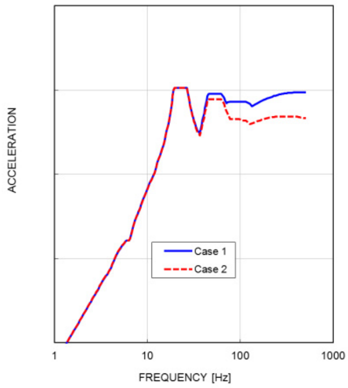

Fig. 9. SG response spectra: main steam nozzle break in Vertical

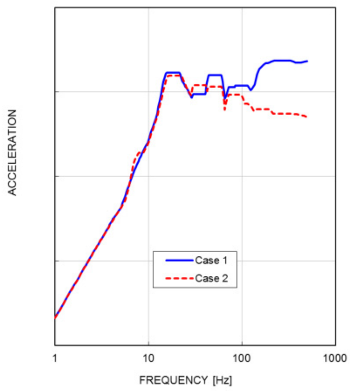

Fig.10. SG response spectra: main steam nozzle break in East-West

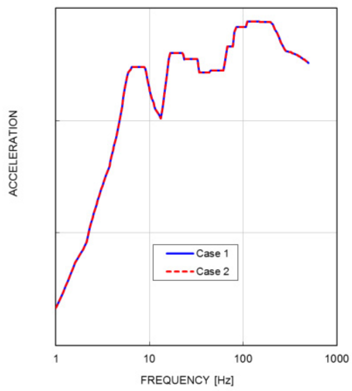

Fig.11. SG response spectra: all case enveloped in North-South

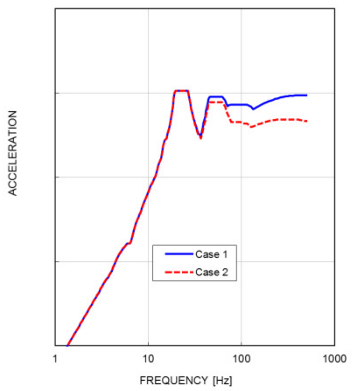

Fig.12. SG response spectra: all case enveloped in Vertical

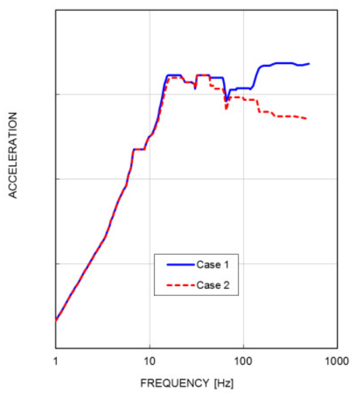

Fig.13. SG response spectra: all case enveloped in East-West

3. Conclusions

The structural analysis was performed to evaluate the blast wave effect on the RCS. The analysis results show that blast wave loads affect the responses in main steam nozzle break case. The supports and nozzle loads of the RCS and the response spectra of the SG are increased. However, the supports and nozzle loads are enveloped by other break cases and only high frequency regions of the response spectra are affected. It is concluded that blast wave loads would not have an impact on the RCS design.

REFERENCES

[1] Y. J. Byun, Y. S. Sul, K. W. Lee, and J. T. Seo, Reactor Coolant System Branch Line Pipe Break Analysis for Shin-Kori Units 3&4, Proceedings of the 18th International Conference on Nuclear Engineering (ICONE18-30066), May 17-21, 2010, Xi'an, China.

[2] U.S. NRC NUREG-0800, “Standard Review Plan Section 3.6.2, Determination of Rupture Locations and Dynamic Effects Associated with the Postulated Rupture of Piping”, Rev. 3, 2016.

[3] Vasilis Karlos, George Solomos Calculation of Blast Loads for Application to Structural Components, Report EUR 26456 EN, 2013.