

## Analysis of a Postulated Pipe Rupture and Subsequent Check Valve Slam of a PWR Feedwater Line

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### SUMMARY

System design criteria employed in the design of pressurizer water reactors (PWR) requires that, for a postulated instantaneous guillotine rupture anywhere in the steam generator feedwater system, no more than one steam generator can be allowed to blowdown. Feedwater systems in many PWR's consist of pipe lines running from the feedwater pumps into a common feedwater header then branching into each steam generator from the header. The feedwater piping to each steam generator contains swing check valves to prevent reverse flow from the steam generator. This activation of some or all of these check valves significantly complicates the system structural analysis in that not only the blowdown forces resulting from the postulated pipe rupture, but also the water hammer loads resulting from closure of the check valve at high reverse flow velocities must be considered.

The loads resulting from system blowdown and check valve closure are axial in nature. Peak loads ranging from 130000 lbs. to 180000 lbs. are not uncommon and are layout dependent. The analysis and design to withstand this transient loading deviates from the usual feedwater line design in that supports are required along the piping axis in the direction normal to the usual seismic supports.

A brief and general discussion of the methods employed in the generation of the thermal-hydraulic loadings is presented. However, the discussion emphasizes the piping and piping support structural design and analysis methods and approaches used in evaluating a selected portion of such a feedwater system.

The design presented in the paper was for an existing, installed system. The discussion details the method of analysis and the approach used to show system acceptability. This includes the type analysis (time-history non-linear), utilization and modification of existing supports, use of pipe whip restraints and various acceptability criteria.

Feedwater system design for this transient is highly dependent on the piping layout. Guidelines are presented, which if used, can significantly reduce the applied loading of this event.

## 1.0 GENERAL DISCUSSION OF THE EVENT UNDER CONSIDERATION

Figure 1 shows a typical schematic diagram of a feedwater system for a Pressurized Water Reactor. (This particular figure is for a four loop plant.) Each portion of a feedwater line supplying a steam generator (SG) contains one check valve. In addition, each branch of auxiliary feedwater line contains at least one check valve. During normal or upset conditions, the design function of these valves is to prevent reverse flow from the SGs during various plant operating transients. An additional function of these valves is to prevent more than one SG from "blowing-down" (depressurizing and emptying of fluid) in the extremely unlikely event of a postulated feedwater line or auxiliary feedwater line rupture. Plant safety analyses for an inadvertent feedwater line rupture rely on the closure of these valves because the standard protection system logic does not provide a signal to close the main feedwater isolation valves in time to prevent the possibility of multiple SG blowdown.

A rupture anywhere in the feedwater system would cause all check valves to rapidly slam shut to prevent reverse flow from the SGs. This valve slam against the reverse flow would generate large pressure pulses and associated thermal-hydraulic (T-H) loads in piping located between the SGs and the check valves (see Figure 1). These large pressure pulses and the associated T-H loads (on the piping) could potentially rupture the piping in this critical area and result in multiple steam-generator blowdowns. In addition if the entire feedwater system is not seismically qualified, a seismic event could initiate a pipe rupture in the non-seismic designed area, which would result in the aforementioned event.

Therefore, for the extremely unlikely possibility of an inadvertent rupture anywhere in the feedwater system, piping between the check valves and the SG for all but one loop must be shown to maintain its pressure boundary integrity. In addition, the check valves must be shown to close and maintain their reverse flow retaining capabilities. This paper focuses on the analysis of one main feedwater line as shown in Figure 2. However, for total plant design, the remaining feedwater lines, the auxiliary feedwater system, and/or any feedwater bypass systems must also be considered.

## 2.0 BREAK SELECTION AND THE NATURE OF THE LOADINGS ENCOUNTERED

Before any analysis could be undertaken, the postulated break location(s) had to be selected. This was required prior to generation of any T-H loads and/or creation of any structural analysis models. Prior analytical studies indicated that the closer a break is postulated to a given SG, the higher the loads would be on the portion of the piping between the break and that specific SG. In addition, as the break moves closer to one SG, the loads are reduced on the piping to the remaining SGs. The break was selected at a point in the piping system which was approximately equidistant from all SGs. Using the resulting T-H loads for a break chosen at this point, as system design loads, piping pressure boundary integrity (between the check valve and the SGs) was then shown for all loops of the feedwater system. If a break then occurs anywhere else in the feedwater system, the loads on the piping to the SG closest to the break would be expected to increase above the design loads but the loads on the piping to the remaining SG would be expected to decrease below the design loads. Therefore, for a break at any point, the piping to the closest SG could potentially fail; however, the piping to the remaining SG would remain intact. The criteria of no more than one SG blowdown for a break anywhere



eigenvectors  $[\phi_a]$  is called the modal matrix.

Matrix Equation (4.1) represents the dynamic equilibrium of the masses of a three-dimensional structure with applied forces in any or all of the coordinate directions. Equation (4.1) can now be transformed into modal coordinates by defining the following linear transformation:

$$[x] = [\phi] [q] \quad (4.3)$$

Where  $[q]$  = modal coordinates

$$\text{and } [\ddot{x}] = [\phi] [\ddot{q}] \quad (4.4)$$

Applying Equations (4.3) and (4.4), and normal mode theory, the actual time responses of the structure for the  $i$ th mass direction are:

$$x_i(t) = \sum_a \phi_{i,a} q_a(t) \quad (4.5)$$

$$\dot{x}_i(t) = \sum_a \phi_{i,a} \dot{q}_a(t) \quad (4.6)$$

$$\ddot{x}_i(t) = \sum_a \phi_{i,a} \ddot{q}_a(t) \quad (4.7)$$

The solution is conducted in two parts using two computer codes. The first program is used to find the frequencies and mode shapes of a three-dimensional structure, including the rotational degrees-of-freedom.

The second program then takes the modal data, generates and solves the modal differential equations which result from time varying applied internal forces.

The program is also capable of solving non-linear elastic systems containing geometric discontinuities (unidirectional supports and supports with gaps) which are attached to ground. These geometric discontinuities are represented by non-linear stiffness elements. The forces arising from these geometric discontinuities are treated as externally applied forces. This Particular analysis contained three linear supports and 27 non-linear, i.e., unidirectional, gapped supports.

The time-history internal forces and displacements are then input into a series of post-processing programs used to determine the maximum forces, moments, and displacements that exist at each end of the piping elements and the maximum loads for the piping supports. The results are saved on magnetic tape for future use in piping stress analysis and support load evaluation.

The loads and stresses resulting from the valve discharge case were combined with the loads and stresses from other loading conditions as defined in plant specific piping design specification. The load combinations are also discussed in Section 5.

## 5.0 SYSTEM DESIGN CONSIDERATIONS AND EVALUATION CRITERIA

### 5.1 SUPPORT SPECIFICATION

Typical systems under consideration have been field installed but the initial design of the system did not consider this transient. The applied T-H loads were generated prior to any structural evaluation. Once the loads are available, the support design loads and maximum allowable support back-up structure and plate loads were reviewed relative to these applied loads. The review was conducted for the express purpose of determining if any supports could be modified to accommodate the applied loads. It was found that 3 existing supports could be used. (The supports are shown on Figure 2.)

Since a limited number of existing supports could be used without major modification, a review was carried out to determine if any other method could be found that would

provide the needed supports for the system. Pipe whip restraints existed on the system and the use of these restraints as supporting members for this event was investigated. A review of the maximum acceptable loads of these pipe whip restraints showed that they had sufficient capacity to dissipate the applied T-H loads. Since the gaps of restraints were very large (> 2"), they could not be directly used as this would permit unacceptable pipe motion prior to engagement. It was decided that the restraints should be shimmed to lower these existing gaps, so as to decrease engagement time, and thereby, aid in supporting the pipe for this transient.

The supports had to be shimmed such that they would not interfere with the thermal motion of the piping during various system operation modes. This was accomplished by conducting a thermal analysis of the piping to determine the applicable direction and minimum acceptable gaps for use in shimming these restraints. It was found that, due to these thermal considerations, some of the pipe whip restraints could be shimmed in only one direction. All pipe whip restraint which were to be shimmed were modeled as non-linear (uni-axial) supports with the applicable thermal gaps applied. This allowed for the direct determination of the effect of the gaps on the piping analysis. It also allowed for the consideration of the impact loading effects on the piping and the supports. Figure 2 shows the location and the directionality of the non-linear supports and Table 2 shows the gaps used in the analysis. The analysis was carried out as described in Section 4 with the non-linear, gapped elements considered as described in that section.

After completion of the initial analysis, the system exceeded the allowable stresses (see Section 5.2.2); additional (new) pipe whip restraints were specified and the analysis rerun. With these changes, the piping system was shown acceptable for this transient. The final support configuration is shown in Figure 2. Table 1 shows the maximum support loads resulting from this analysis. It should be noted that certain supports did not close the minimum gaps and, therefore, had no effect on the analysis. The use of the non-linear technique allowed specification of all possible pipe whip restraints, which could act as supporting members. If certain supports were not activated, this is accounted for in the analysis runs. Therefore, this technique eliminates the need for costly analysis iterations (to determine active supports) which would be required by linear analysis. Table 3 shows a sampling of the piping stresses resulting from the analysis.

The use of pipe whip restraints appropriately shimmed provided significant cost benefits in doing this redesign. The shimming of the restraints provided adequate support and eliminated the need to do extensive modification to the existing supports. In addition, the pipe whip restraints were shimmed so as not to affect the thermal piping growth and, therefore, no reanalysis and/or requalification for the applicable thermal and other static loading cases was required. When additional supports were required, the use of gapped restraints allowed the supports to be constructed from relatively inexpensive and easy to obtain structural steel and, again, did not affect the previous static analysis.

## 5.2 EVALUATION CRITERIA

### 5.2.1 GENERAL

The feedwater line rupture event was considered a faulted condition (for any plant, the load classification for this event must be obtained from the FSAR and/or piping

design specification). The applicable load combinations considered were:

$$P + DWT + (FR^2 + SSE^2)^{1/2} \quad \text{[Piping]} \quad (5.1)$$

$$DWT + TH + (FR^2 + SSE^2)^{1/2} \quad \text{[Supports]} \quad (5.2)$$

$$P + DWT + TH + (FR^2 + SSE^2)^{1/2} \quad \text{[Active Valves]} \quad (5.3)$$

P = Maximum pressure

DWT = Weight loads

TH = Thermal loads

FR = Feedline rupture loads

SSE = Safe Shutdown Earthquake loads

### 5.2.2 PIPING EVALUATION CRITERIA

The Class 2 and B31.1 faulted limits specified in the applicable Code (References 1 and 2) were initially used in the piping evaluation. The basic equation to be met was:

$$\frac{PD_0}{4t} + \frac{.75i (M_i)}{Z} \leq 2.4 S_h \quad (5.4)$$

where the parameters are as defined in the Code (References 1 and 2).

If this equation was exceeded the piping stresses were reevaluated using limit load failure theory with primary stress indices and a  $2.0 S_y$  stress limit, i.e.,

$$B_1 \frac{PD_0}{Zt} + B_2 \frac{M_i}{Zp} \leq 2.0 S_y \quad (5.5)$$

where the parameters are defined in NB-3600 of the Code (Reference 1).

If this equation was also exceeded, limit level failure theory and the faulted evaluation of Appendix F of the Code (Reference 1) was applied, i.e.,

$$B_1 \frac{PD_0}{Zt} + B_2 \frac{M_i}{Zp} \leq 3.0 S_m \quad (5.6)$$

where the parameters are defined in Appendix F of the code (Reference 1).

In addition actual field measured piping properties (OD's, wall thickness, etc.) were used. Also finite element and test results for certain piping components were used. (See References 3 and 5.)

The maximum peak pressure was shown to be less than the allowable working pressure as defined in the applicable piping evaluation code.

The above criteria was applied to piping between the check valve and SG. For the upstream piping (between the break and the check valve), this criteria was initially applied. This criteria could not be met (upstream) at all points. A detailed evaluation was undertaken to show the piping would not form any plastic hinges. By showing the piping met the applicable plastic hinge limits, it could be insured no pipe whip would occur and no subsequent damage would be incurred by the downstream piping and neighboring piping systems. A detailed discussion of this subject is beyond the scope of this paper. No pressure boundary requirements need be met by the upstream piping as failure of the pressure boundary of this piping would not affect the multiple SG blowdown criteria.

### 5.2.3 SUPPORT EVALUATION

The evaluation of supports was carried out by comparing the calculated support loads to the maximum allowable component loads. In addition, actual support component test data was obtained and used in support evaluation. All work was performed in accordance with the applicable support evaluation rules found in References 1 and 4. Pipe whip restraint qualification was conducted in a similar manner.

#### 5.2.4 CHECK VALVE EVALUATION

The check valves were evaluated using the applicable allowable operability/ function capability nozzle limits as supplied by the various valve manufacturers. As the loads generated from the blowdown and check valve slam loadings are normally very severe and significantly above those loads that the valves were originally qualified for, an update of the valve stress report had to be performed. The update was performed by the same analytical method contained in the original report, but including any loads that may be generated from the postulated pipe rupture. The impacting load at the closure of the swing disc was also considered. The evaluation showed that the original design limits are met.

#### 6.0 DESIGN CONSIDERATIONS FOR FUTURE SYSTEMS

As a result of this work, several factors became apparent which should be considered in future design of feedwater systems:

1. Long straight runs of piping should be avoided as the hydraulic loads tend to increase as the length of a given run of straight pipe increases.
2. The amount of piping between the SG and check valve should be minimized as the check valve slam loads tend to increase as this amount of piping increases.

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**Table 1 - Maximum Support Loads (Linear and Non-Linear Supports)**

Node Point	Support Restraining Direction Sur. Type	SUPPORT LOADS (in KIIPS)					
		+Y	-X	+Y	-Y	+Z	-Z
1	NL	---	---	---	---	---	0.
2	NL	---	0.	---	215.	---	---
3	NL	---	---	349.	---	300.	0.
4	NL	---	---	---	---	---	311.
5	NL	251.	321.	---	---	---	---
6	NL	194.	228.	---	---	318.	---
7	NL	0.	44.	224.	237.	---	---
8	L	60.	60.	80.	80.	34.	34.
9	L	161.	161.	.03.	103.	220.	220.
10	NL	155.	---	---	---	---	217.
11	NL	140.	114.	167.	---	140.	114.
12	L	---	---	60.	60.	68.	66.
14	NL	---	---	---	---	---	234.
15	NL	---	---	---	---	183.	---
16	NL	---	---	50.	61.	105.	97.

L = Linear Support  
 NL = Non-Linear Support  
 --- = No Support in the Identified Direction

**Table 2 - Support Gaps Used in the Analysis for Non-Linear Supports (Pipe Whip Restraints)**

Node Point	Direction	NOMINAL SUPPORT GAPS USED (in INCHES)					
		+X	-X	+Y	-Y	+Z	-Z
1	---	---	---	---	---	---	7/8
2	---	---	1-7/16	---	1/16	---	---
3	---	---	---	1/16	---	1/16	11/16
4	---	---	---	---	---	---	1/16
5	1/16	13/16	---	---	---	---	---
6	1/16	5/16	---	---	---	7/16	---
7	1/4	1/16	1/16	1/16	---	---	---
10	1/16	---	---	---	---	---	1/16
11	1/16	7/16	1/16	---	---	1/16	7/16
14	---	---	---	---	---	---	1/16
15	---	---	---	---	---	1/16	---
16	---	---	1/16	1/16	1/8	1/16	---

**Table 3 - Typical Stresses Resulting from the analysis**

Element Type	Nd. Pt.	Dev. Stress (KSI)	Indices Used	Stress Criteria	Allowable Stress (KSI)
LRE	A	37.5	P	2.0 Sy	57.0
LPE	B	38.5	P	2.0 Sy	57.0
2" SM Half Coupling	C	51.8	P	2.0 Sy	57.0
LRE	D	46.1	P	2.0 Sy	57.0
LRE	E	29.3	AP	2.4 Sh	36.0

Sy = Yield Stress at the appropriate temperature  
 Sh = Class 2 Material allowable at the appropriate temperature  
 LRE = Long Radius Elbow  
 P = Limit Load type Primary Stress Indices used in Stress Calculations  
 AP = Class 2 Stress Intensification Factors used in Stress Calculations, i.e. .75x for Primary Stress approximation. (i = the appropriate Class 2 stress intensification factor)



