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TECHNICAL CONSIDERATIONS FOR FLEXIBLE PIPING DESIGN IN NUCLEAR POWER PLANTS

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TECHNICAL CONSIDERATIONS FOR FLEXIBLE PIPING DESIGN IN NUCLEAR POWER PLANTS*

ABSTRACT

The overall objective of this research project is to develop a technical basis for flexible piping designs which will improve piping reliability and minimize the use of pipe supports, snubbers, and pipe whip restraints. The current study was conducted to establish the necessary groundwork based on the piping reliability analysis.

A confirmatory piping reliability assessment indicated that removing rigid supports and snubbers tends, to either improve or affect very little the piping reliability. We then investigated a couple of changes to be implemented in Regulatory Guide (RG) 1.61 and RG 1.122 aimed at more flexible piping design. We concluded that these changes substantially reduce calculated piping responses and allows piping redesigns with significant reduction in number of supports and snubbers without violating ASME code requirements. Furthermore, the more flexible piping redesigns are capable of exhibiting reliability levels equal to or higher than the original stiffer design.

An investigation of the malfunction of pipe whip restraints confirmed that the malfunction introduced higher thermal stresses and tended to reduce the overall piping reliablity. Finally, support and component reliabilities were evaluated based on available fragility data. Our result indicated that the support reliability usually exhibits a moderate decrease as the piping

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flexibility increases. Most on-line pumps and valves showed an insignificant reduction in reliablity for a more flexible piping design.

1. INTRODUCTION

Nuclear power plant components, including piping systems, are required by law to be designed to withstand the individual effects, as well as the appropriate combination of effects, due to normal operation, natural phenomena, and postulated accidents. The common practice in designing nuclear piping systems is to add support devices, such as rigid supports and snubbers, and pipe whip restraints to withstand effects of large dynamic loads caused by natural phenomena and postulated accidents. Events associated with natural phenomena and postulated accidents are random in nature and are often accompanied by great uncertainties. In order to accommodate these uncertainties, conservative design procedures have been adopted for nuclear piping systems and usually have resulted in stiff piping designs with excessive use of support devices. Excessive use of support devices, however, has created various problems:

A. Increased cost

B. Poor access for plant inspection and maintenance

C. Increased personnel exposure to radiation

D. Decreased piping reliability due to:

   a. higher thermal strtesses in stiff piping

   b. malfunction of snubbers

   c. malfunction of pipe whip restraints

Clearly, problems created by excessive use of support and restraint devices can be mitigated, if not completely eliminated, by adopting piping designs which include minimal use of support and restraint devices. Improved design requirements and criteria are needed in order to arrive at such piping designs.

The research project described in this report was initiated at Lawrence Livermore National Laboratory (LLNL) by the United States Nuclear Regulatory Commission (NRC). The objective of this project is to develop a technical basis for flexible piping designs that minimize the use of rigid pipe supports, snubbers, pipe whip restraints, etc. Highlights of the research project are presented in this paper. Readers are referred to Ref. 1 for detailed information with regard to the research project.

2. APPROACH

A typical piping system usually consists of the piping, support devices (namely, rigid supports and snubbers), on-line components (such as, pumps and valves), and, in many cases, pipe whip restraints. The piping flexibility can be changed by adding or removing rigid supports and snubbers. Malfunctions of snubbers and pipe whip restraints can also affect the piping flexibility. We feel that a rational approach for developing a technical basis for flexible piping designs should be based on a reliability consideration. Accordingly, reliability analyses were conducted for a variety of piping systems.

Current design criteria for piping, which address specific load types individually, evolved under the presumption that higher seismic margins necessarily improve plant reliability. Conservative design against earthquake loads has relied increasingly on rigid supports, snubbers, and other types of seismic restraints to stiffen piping systems. The resultant decrease in flexibility, however, is likely to cause higher normal operating stresses because of the restraint of thermal expansion. Furthermore, because of the large uncertainty inherent in predicting seismic effects (compared to that in predicting themal effects), seismic loads dominate the design even though seismic loads occur very infrequently. As a results, stiffening a piping system to improve its resistance to seismic loads may actually decrease its overall reliablity during normal operation.

The first step undertaken by this research work was to assess the impact on the piping reliability due to the increased piping flexiblity for a number of piping systems. The goal is to confirm that a flexible piping design with reduced seismic restraints (both rigid supports and snubbers) can be more reliable than or as reliable as a stiff piping design. In this confirmatory study, we dealt only with the "piping" portion of a piping system. The reliabilities associated with pipe supports and on-line components as affected by the piping flexibility would be treated as separate tasks.

In order to quantify the piping reliability, pipe failure probabilities were computed. Pipe failure was assumed to be caused by fatigue crack growth at pipe weld joints. Two types of failure modes were considered, i.e., a through wall crack (leak) and a complete pipe severance (break). The pipe failure probability was estimated by applying a Monte Carlo method with a stratified-sampling scheme to simulate the life histories of the piping system (Ref. 2).

Selected piping systems with related design data were collected from real nuclear power plant designs. Flexible piping designs were created from the existing designs by removing rigid supports and/or snubbers. Piping stresses for various designs were calculated for the reliability assessment. Figure 1 illustrates a safety injection line from a PWR plant, which is one of the piping systems we analyzed.

This assessment recognizes the characteristic difference between regular pipe supports and snubbers. While removal of regular pipe supports changes both seismic stress and thermal expansion stress in a piping system, removal of snubbers affects only seismic stress. However, a piping system, including snubbers, may not exhibit the desired reliability because snubbers are known to have a high failure rate. The possibility of snubber malfunction is incorporated in this assessment.

We demonstrated in Step 1 the desirability of the flexible piping design based on the piping reliability consideration. In order to achieve more flexible and reliable piping designs, changes are needed with regard to current design requirements, criteria, and practices. In the next step, the current study investigated the impact on piping designs due to two changes to the NRC Regulatory Guides 1.61 and 1.122 (Refs. 3 & 4), dealing, respectively, with damping values and broadening floor response spectra for piping systems. These two regulatory guides introduce substantial conservatism in the seismic spectrum analysis and result in the excessive use of snubbers and rigid supports in nuclear power plant piping systems. Recently, the NRC has evaluated these changes which were initially proposed by the Steering and Technical Committees on Piping Systems of the Pressure Vessel Research

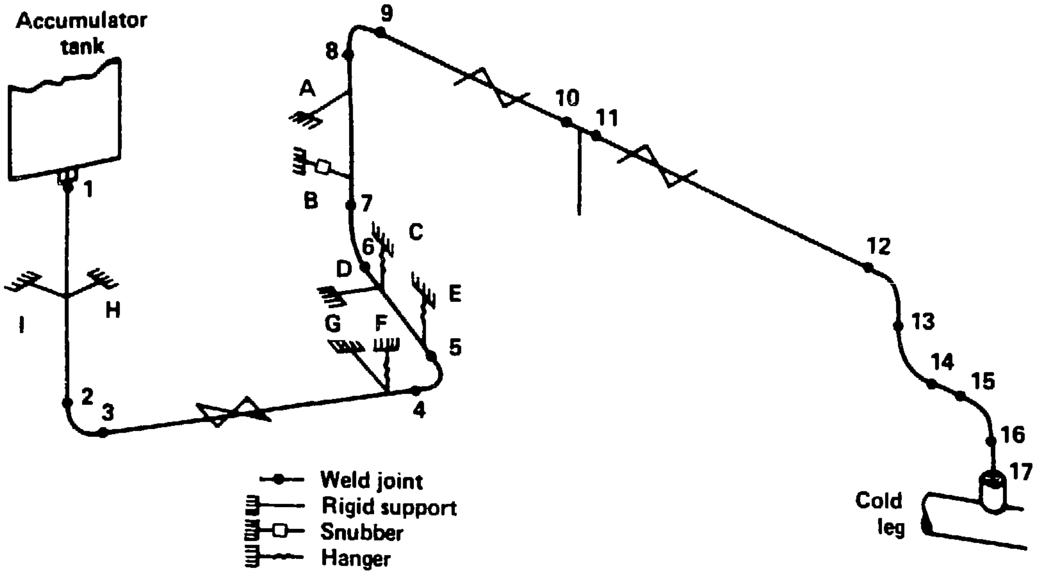


Figure 1. Safety Injection Line from a PWR Plant

Committee (PVRC) in order to reduce conservatism (Ref. 5). Figure 2 illustrates both the original RG 1.61 damping and the PVRC damping while Fig. 3 explains the PVRC proposed change to R.G. 1.122.

In this investigation, we quantified the reduction in calculated piping responses resulting from the changes. We showed that the potential benefit of the changes was to allow a redesign of the piping system where a substantial number of snubbers and rigid restraints could be removed without causing the calculated stresses in the pipe to exceed code allowables. We also showed that the more flexible redesign is acceptable based on a reliability analysis.

In the third step, we dealt with the malfunction of pipe whip restraints. We investigated in this step the situation where the pipe comes in contact with a restraint device during normal operation due to an imperfect installation. We calculated the actual stress distribution caused by the malfunction. We assessed the safety impact on the piping sytem by conducting a piping reliability analysis with and without the malfunction. The purpose was to confirm that the malfunction of pipe whip restraints introduces higher thermal stresses and reduces the overall piping reliability.

Having demonstrated the desirability of flexible piping design based on reliability consideration on the behavior of the piping itself, this study also evaluated changes in reliability for pipe supports as well as on-line components as the piping design is made more flexible. Support and component reliabilities were evaluated based on available fragility data and were accomplished in Steps 4 and 5. The outcome of the support and component reliability evaluation was expected to identify precautions and restrictions that should be exercised in arriving at a flexible piping.

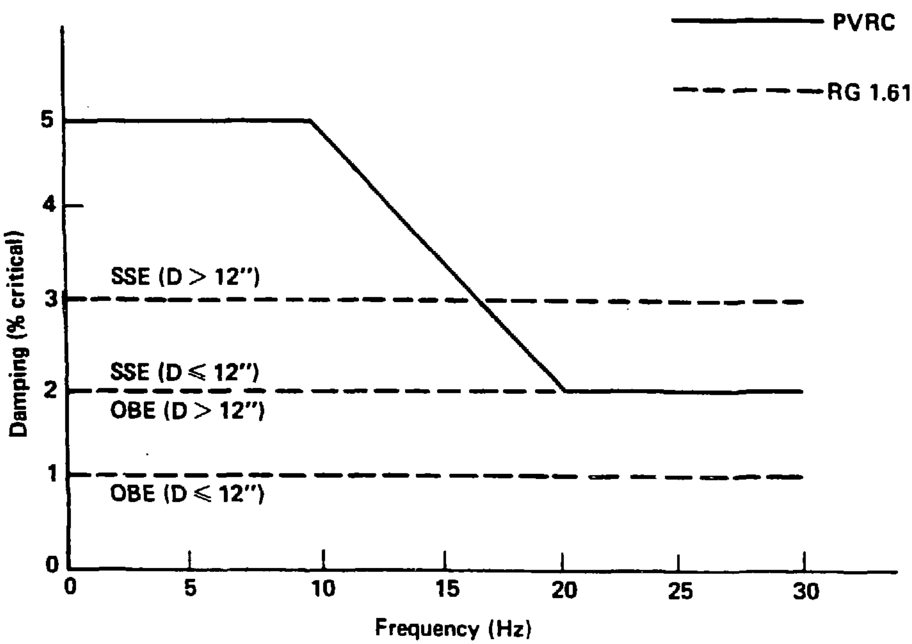
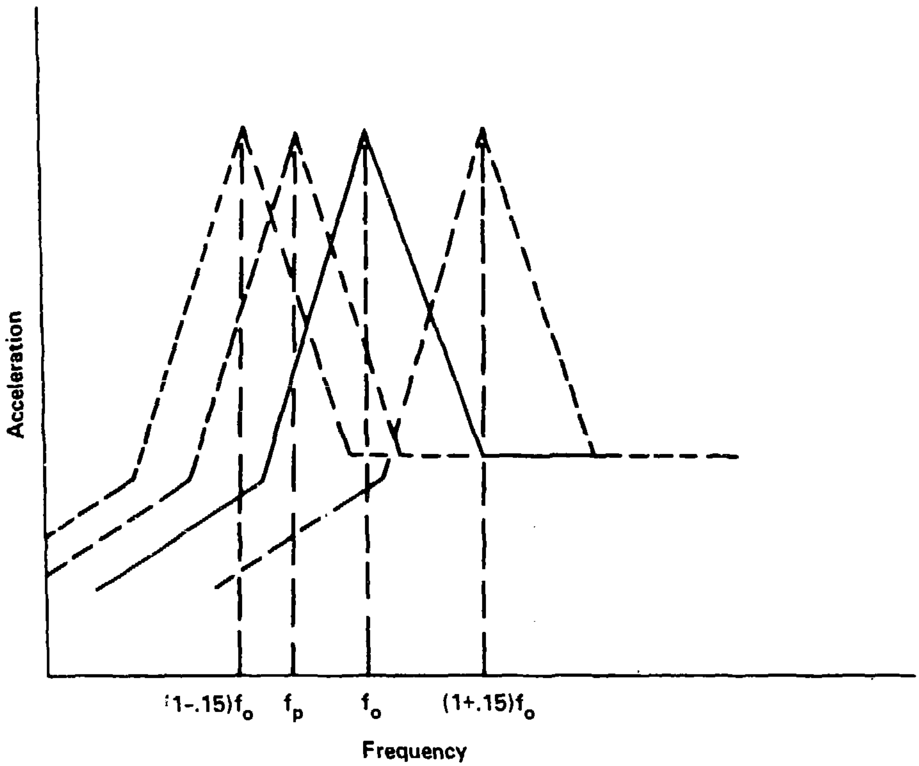


Figure 2. PVRC Proposed Damping vs. RG 1.61 Damping



PVRC Proposed Procedure:

1. Identify piping modes and frequencies lying in the ±15% range of the peak frequency of the unbroadened spectrum, f_o.
2. Sfift the spectrum to match the peak at the following frequencies: f_o, $(1\pm.15)f_o$, and each of the piping frequencies, f_p.
3. Perform response spectrum analysis for each shifted spectrum and use the maximun response calculated.

Figure 3. PVRC Proposed Change to RG 1.122.

3. CONCLUSIONS

Based on our observation, the change in piping reliability is not very sensitive to the change in piping flexibility for the cases we have studied. Consequently, the piping reliability is either improved or affected very little by the increased piping flexibility as a result of removing rigid pipe supports and/or snubbers. Typical results for the safety injection line (see Fig. 1) are shown by Table 1. We have also ovserved that pipe failure probabilities are generally small, i.e., approximately 10^{-9} for "break" and 10^{-6} for "leak". We therefore conclude that the flexible piping design is desirably based on the reliability consideration although the flexible piping design also offers many other benefits.

An increase in piping reliability for a flexible piping design is generally attributed to relaxation of the thermal expansion stress for flexible piping, although the seismic stress may be increased by piping flexibility. The thermal stress is usually caused by plant operation and its cyclic effect is the major driving force for fatigue crack growth which may essentially cause the pipe to fail. On the other hand, seismic stress caused by an earthquake is a natural phenomenon with low probability of occurrence. Therefore, the contribution to pipe failure due to seismic loads is of secondary importance, since the event occurrence rate is considered in the piping reliability analysis.

Another reason why the flexible piping design may improve the piping reliablity is due to the fact that a flexible piping contains less snubbers. Snubbers are known to have a high rate of malfunctioning. The malfunction of

Table 1. Pipe Break Probability for Various Piping Design of the Safety Injection Line.

Piping Design	Pipe Break Probability
LC1	2.8×10^{-8}
LC2	1.3×10^{-9}
LC3	6.6×10^{-8}

Note: LC1-Existing design

LC2-Snubber B removed

LC3-Snubber B and lateral Supports D, G, H, I removed snubbers tends to introduce unexpected and undesirable stresses in the pipe and increases the pipe failure probability.

In order to achieve more flexible and reliable piping designs changes are needed with regard to current design requirements, criteria, and practices. The current study investigated the impact on piping designs due to two changes proposed by the PVRC Steering and Technical Committees on Piping Systems with respect to the NRC Regulatory Guides 1.61 and 1.122. Our study has demonstrated that these changes can substantially reduce calculated piping response and, consequently, allow piping redesigns with significant reduction in the number of supports and snubbers without violating ASME code requirements. Typical results are illustrated by Fig. 4 for the portion of an auxiliary feedwater (AFW) system in a PWR plant as shown by Fig. 5. Furthermore, flexible piping redesigns are capable of exhibiting reliability levels equal to or higher than the original stiffer designs (see Table 2).

Although we have demonstrated that piping systems can be made more reliable by adopting flexible piping designs based on the piping reliablity analysis conducted in this study, we do caution that changes adopted in the piping design procedure to increase the piping flexiblity usually result in greater displacements. For this reason, the NRC may need to consider the implementation of certain displacement criteria or requirements to confine piping displacements.

As we discussed previously, pipe whip restraints, if not properly located or installed, can cause safety concerns as well as other problems. In this study, we examined the malfuncton of pipe whip restraints based on its impact on piping reliability. We confirmed that the malfunction introduced higher

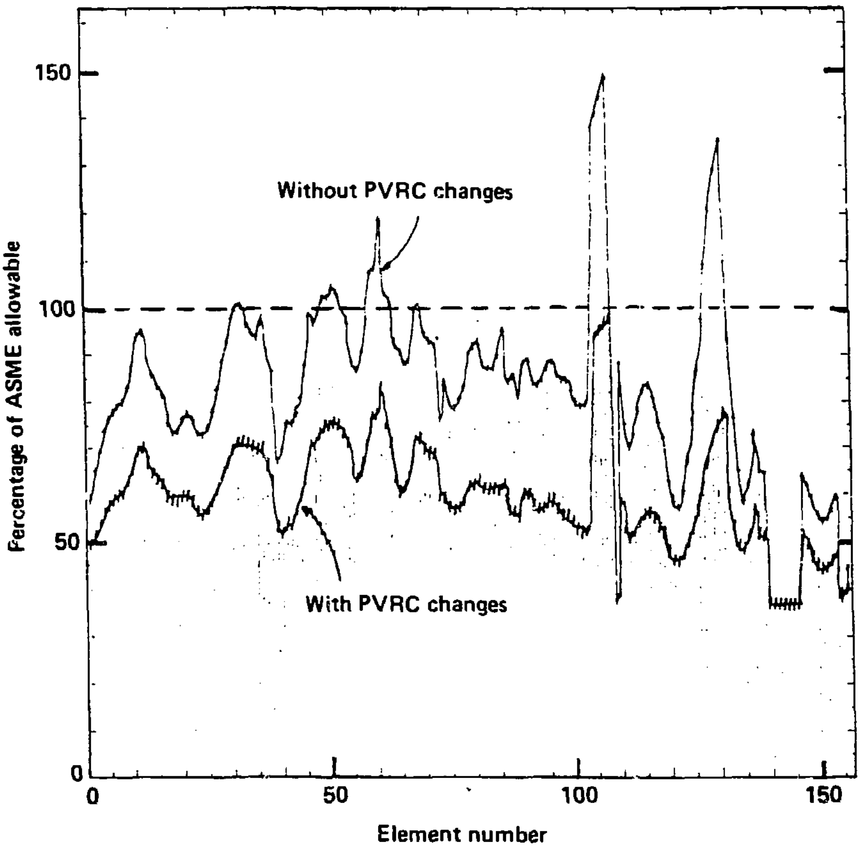


Figure 4. Summary of ASME Code Evaluation

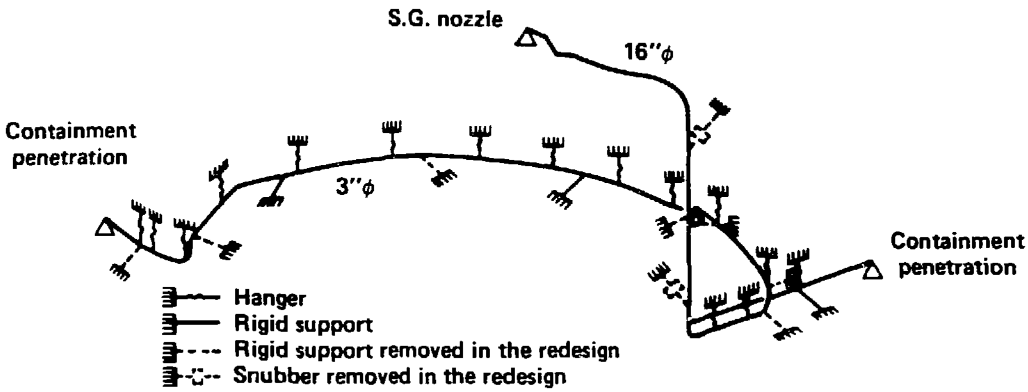


Figure 5. AFW Line inside Containment of a PWR Plant

Table 2. Pipe Failure Probabilities for the AFW System.

Piping Design	Break Problem	Leak Problem
Original	0.327×10^{-12}	1.022×10^{-8}
Flexible	0.616×10^{-12}	0.836×10^{-8}

thermal stresses and tended to reduce the overall piping reliability. We discovered that, typically, pipe break probability increases from 10^{-12} to 10^{-11} and leak probability increases from 10^{-8} to 10^{-6} for the AFW system due to the malfunction of pipe whip restraints. Our results provided additional support to other research efforts aimed at the elimination of the pipe break as a design requirement which leads to the need of pipe whip restraints.

Since pipe supports and on-line components (such as pumps and valves among others) are important parts of a piping system, the effects of increased piping flexibility on the reliability of supports and components were investigated. Our results indicated that the support reliablity usually exhibits a moderate decrease as the piping flexibility increases. We feel that the supports in a flexible piping design need to be either upgraded or subjected to further investigation.

For large components, such as steam generators, pressurizers, and large pumps, the global effect concerning the component support failure due to increased nozzle loads was evaluated. We found that in general the global effect is rather insignificant. We feel, however, the local effect at the vicinity of the nozzle may need to be further investigated. Without such an investigation, we suggest that removing pipe supports which are close to nozzles should be done with extreme care.

For self-supporting on-line valves, we discovered that the valve acceleration may or may not increase with the piping flexibility. Nevertheless, valves usually have sufficient design margins to accommodate the higher acceleration and are able to maintain the functionality. The problem in this case is the increased valve displacement usually associated with a flexible piping design. Specific design consideration may be needed in order to limit the valve displacement.

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