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Reliability Analysis of Stiff Versus Flexible Piping— Status Report

S. C. Lu and C. K. Chou

Prepared for
U.S. Nuclear Regulatory Commission

MASTER



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Reliability Analysis of Stiff Versus Flexible Piping— Status Report

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ABSTRACT

Conservative design procedures adopted for nuclear piping systems usually result in stiff piping designs that use excessive support devices such as rigid supports and snubbers. Use of these piping support devices has created safety concerns. This report describes the interim result for a piping research project conducted at Lawrence Livermore National Laboratory (LLNL) for the U.S. Nuclear Regulatory Commission (NRC).

The overall objective of this research project is to develop modified design requirements and criteria 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 for this work based on the piping reliability analysis.

A confirmatory piping reliability assessment for stiff versus flexible piping systems indicated that removing rigid supports tends, in general, to reduce thermal stress but to increase seismic stress in the pipe. As a result, piping design can be made more reliable by some reduction of rigid supports. We also observed that piping design using snubbers among support devices may not exhibit the intended reliability because snubbers often fail to perform the desired function. It was demonstrated that certain piping systems with snubbers removed actually exhibit higher reliability than do those of the original design.

The Steering and Technical Committees on Piping Systems established by the Pressure Vessel Research Committee (PVRC) have investigated changes to be implemented in Regulatory Guide (RG) 1.61 and RG 1.122 aimed at more flexible piping design. An independent impact assessment conducted by this project concluded that: (1) PVRC proposed changes substantially reduce calculated piping responses; (2) proposed changes allow piping redesigns with significant reduction in number of supports and snubbers without violating ASME code requirements; and (3) the more flexible piping redesigns are capable of exhibiting reliability levels equal to or higher than the original stiffer design.

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EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) has engaged the Lawrence Livermore National Laboratory (LLNL) to perform a nuclear piping system reliability analysis comparing stiff versus flexible piping. The overall objective of this project is to develop modified design requirements and criteria which will improve piping reliability and minimize the use of pipe supports, snubbers, and pipe whip restraints.

The project is divided into two phases: Phase 1, the actual reliability analysis of stiff versus flexible piping; and Phase 2, the development of design criteria for improved piping design of future nuclear power plants, as well as for guidance in the modification of existing plants. During Phase 1, the necessary groundwork for the completion of the study is established. Specifically, our goals include the following: 1) to confirm that flexible piping design achieved through the reduction of piping supports and restraints is generally more reliable than stiff piping design; 2) to find a piping redesign which offers optimum flexibility and then to assess its reliability when subject to given changes in design requirements, criteria and practice; and 3) to develop a better understanding of the ways in which each design element contributes to current piping problems. When these goals have been met, we hope to identify feasible changes to piping design requirements, criteria and practice. In this interim project report, we present the work accomplished during FY 82 and FY 83.

We performed a corroborative piping reliability assessment of stiff versus flexible piping systems which indicated that the removal of rigid supports generally reduces thermal stress but increases seismic stress in the pipe. We concluded that by some reduction of rigid supports, piping design can be made more reliable. We observed that snubbers used as piping support devices may not always perform their desired function, and certain piping systems where snubbers have been removed actually exhibited higher reliability.

Our findings generally favored the flexible piping design. However, certain changes in the piping design procedure are required in order to allow nuclear piping systems to be more flexibly designed. The Steering and Technical Committees on Piping Systems established by the Pressure Vessel Research Committee (PVRC) have investigated changes to be implemented in the NRC Regulatory Guide (RG) 1.61 and 1.122 specifying, respectively, damping and floor response spectra to be used in the seismic design of nuclear power plants. These changes were adopted by our study, and their impact to piping design was evaluated. We subsequently concluded that: 1) these changes were able to substantially reduce calculated piping responses while retaining sufficient margins of conservatism; 2) the proposed changes allowed piping redesigns with a significant reduction in the number of seismic supports without violating ASME code requirements; and 3) the more flexible piping redesigns were capable of exhibiting reliability levels equal to or higher than the original stiffer designs.

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 problems.

We have three design options when designing piping systems to withstand the dynamic loads associated with a natural phenomenon (such as a seismic event) under the constraint of a limited space environment. These options are:

- 1) To add rigid supports to resist the large dynamic loads caused by a seismic event.
- 2) To use devices, such as snubbers, that not only allow free thermal movement during normal operation but also provide supports for the large dynamic loads caused by a seismic event.
- 3) To use a combination of the above.

The first design scheme (the addition of rigid supports), results in more rigid piping systems. A negative consequence of this design is that the increased thermal stress during daily normal operation may reduce the reliability of piping systems during the plant's lifetime.

The second design scheme (the use of snubbers to absorb energy generated by seismic events) results in several different problems. For example, the snubbers may not function properly during a seismic event. Actual test data on snubbers clearly indicates the reliability for these devices is low enough to warrant our concern. The failure of snubbers to function properly during a seismic event will cause force re-distribution. Consequently, the piping system may be overly stressed in a way not accounted for in the original design. Thus, this becomes a safety concern.

The third design scheme (a combination of both schemes), could result in both negative effects.

Postulated accident events, such as large Loss-of-Coolant Accidents (LOCA), will also introduce large dynamic loads to the piping system design. Consequently, the piping system design will have to accommodate these large forces, and the same problems as discussed above will have to be considered. In addition, pipe whip restraints will have to be provided in the piping system at the location of predicted ruptures to prevent a chain reaction accident, to protect the safety-related components, and to limit fluid flow area.

Pipe whip restraints normally are designed to allow free thermal movement, and the gap between the restraint device and the piping itself normally is designed as small as possible to reduce pipe whip impact loads. The specified clearance is sometimes designed as small as 1/16". This specification also causes complications. For example:

- 1) The pipe could come in contact with a restraint device during normal operation due to imperfect installation. As a result, the piping system will experience higher thermal stress, and the actual stress distribution will be different from that of the original design. Both situations may present serious safety concerns.
- 2) The gap requirement specified in the design may be satisfied during construction by forcing the pipe to fit, thereby introducing large cold spring strain in the pipe. Subsequently, additional stress of an unknown magnitude and not anticipated in the design will be introduced on the piping system. The possible consequences resulting from this situation are unknown.
- 3) The location of the postulated break may not be correct. When a pipe rupture actually occurs at a location different from the postulated break, the piping system and nearby safety components will not be properly protected. Very serious cases have occurred in nuclear plant construction. It is interesting to note that postulated pipe break locations are often determined by criteria based on the failure mechanism due to mechanical stress. By reviewing piping failure data, we have observed that piping systems normally will not fail under mechanical stress alone. Instead, the major failure mechanisms are thermal fatigue, corrosion, and vibration caused by component operation or fluid in the piping systems. The situation can be much worse if misalignment or residual stress is introduced during construction or fabrication. Piping failures normally occur at the terminal ends or at weld joints, especially those where elbows, tees, reducers and component nozzles are located. Therefore, we feel the current criteria for predicting the possible break locations can be significantly improved.
- 4) A combination of any two or three possibilities may exist as stated above.
- 5) Earthquakes may cause relative movement between the pipe and pipe whip restraints and, therefore, unpredicted high frequency vibration.
- 6) The restraint device may cause an increase in heat loss from the pipe to the containment because the pipe cannot be properly insulated at locations of pipe whip restraints.
- 7) The restraint device may block the access either for the plant operation or for the in-service inspection.

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 overall objective of this project is to develop modified design requirements and criteria which will improve piping reliability and minimize the use of rigid pipe supports, snubbers, pipe whip restraints, etc. The results of this study will provide input to the NRC Piping Review Committee for further piping design regulation changes.

This research project is conducted in two consecutive phases. The overall objective of developing improved piping design requirements and criteria will essentially be accomplished in Phase 2. We feel strongly that a rational approach for developing design requirements and criteria should be based on a reliability consideration. Therefore, in Phase 1 of this project, our effort is to establish the necessary groundwork by conducting reliability analyses for various piping systems.

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.

In the current study, we deal only with the piping reliability with regard to changes in piping flexibility resulting from the removal of rigid supports and snubbers. The study also includes a limited treatment of the snubber malfunction. Component and pipe support reliability as affected by piping flexibility and malfunctions of snubbers and pipe whip restraints will be treated in a more extensive assessment to be conducted at a later stage of this project.

In Section 2 of this report, we describe major tasks and methods of analyses associated with the current study. Section 3 summarizes results and discussions. In Section 4, we present conclusions.

2. APPROACH

In this section, we describe two major tasks conducted in the current study. For each task, we discuss piping models, loading conditions, and methods of analysis used in the stress calculation and the piping reliability evaluation.

2.1 Confirmatory Piping Reliability Assessment of Stiff versus Flexible Piping

The major work for this task is to assess and compare pipe failure probabilities for various piping designs to confirm that flexible piping design as a result of reducing piping supports can be more reliable than stiff piping design. Pipe failure is assumed to be caused by fatigue crack growth at pipe weld joints. Failure is defined as either a through wall crack (leak) or a complete pipe severance (break). The failure probabilities are estimated by applying a Monte Carlo method to simulate the

life histories of the selected weld joints of the piping system. Loading conditions considered include non-seismic loads (such as the thermal expansion effect, pressure and dead weight) and seismic excitations, i.e., earthquakes. The numerical calculation was accomplished by execution of the computer code, PRAISE, which stands for Piping Reliability Analysis Including Seismic Events.¹

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 or snubbers. Piping stresses for various designs were calculated for the reliability assessment. The number and locations of supports or snubbers to be removed were determined without regard to whether these flexible piping designs satisfy current design requirements, mainly, stress limits specified by ASME Boiler and Pressure Vessel Code.²

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.

For each selected piping system, a piping reliability analysis was conducted for the existing final design as well as for three recreated piping configurations to represent the initial design, an intermediate design, and a piping design with snubbers removed. In the following, we discuss piping models, loading conditions, and methods for both the stress analysis and the piping reliability analysis in more detail.

2.1.1 Piping Models

We selected three piping systems from two pressurized-water-reactor (PWR) plants for the confirmatory piping reliability assessment. Three piping models were subsequently developed from the respective piping systems for use in conducting the necessary analyses.

Model 1 is a 14-in. pressurizer surge line as found in Plant A. The surge line is attached to the bottom of the pressurizer and connects the pressurizer to the hot leg of a reactor coolant loop (RCL). The mathematical model used for the stress analysis employs straight and curved pipe elements to represent the 14-in. pipe. The model also includes the pressurizer, which is presented by a series of straight pipe elements. Pipe supports, hangers, and snubbers are modeled with truss and beam elements, as are the pressurizer supports. This model has three vertical hangers, one lateral rigid support, and two snubbers. The pipe has an outside diameter of 14.0 in. and thickness of 1.406 in. The material is ASTM A-376 Type 316 austenitic stainless steel.

Model 2 is a 10-in. safety injection line as found in Plant B. The 10-in. pipe in Model 2 runs between the accumulator tank and the cold leg of the RCL. Model 3 is a portion of the pressurizer spray line as found in Plant B. This spray line extends from the cold leg of the RCL to the top of the pressurizer. Model 3 consists of a branch line of the

pressurizer spray line extending from the pressurizer spray nozzle to the branch joint. These two models were provided by the Duke Power Company. The modeling technique is considered similar to that of Model 1 developed at LLNL. Although we are interested only in the 10-in. run of the safety injection line, a 6-in. branch line was also included in the stress analysis. Similarly, the entire pressurizer spray line was considered in calculating piping stresses in the branch line represented by Model 3.

The 10-in. pipe of Model 2 has three vertical hangers, five lateral rigid supports, and one snubber. The outside diameter is 10.75 in., and the thickness is 0.365 in. The portion of the pressurizer spray line has three vertical hangers, seven lateral rigid supports, and nine snubbers. The portion of the pipe near the pressurizer has an outside diameter of 4.5 in. and thickness of 0.531 in. The rest of the branch pipe has an outside diameter of 6.625 in., and a thickness of 0.718 in. The material for both piping models is austenitic stainless steel. The three piping models are illustrated by Figs. 1, 2, and 3.

2.1.2 Stress Analysis

The approach selected to estimate pipe failure probabilities requires an estimate of piping stresses arising from all relevant loads during the plant's lifetime. We considered pressure, dead load, restraint of thermal expansion, and seismic load in the stress analysis.

For model 1, the stress analysis was conducted at LLNL. Dead load and thermal expansion stresses were calculated by the finite element method using the SAP4 computer code.³ Pressure stress was computed using formulas. The seismic stress represents a statistical median value resulting from a time-history analysis executed through the SMACS computer code.⁴ For the pressurizer surge line, we considered only the dominant heat-up and cool-down cycle in calculating the thermal stress. The occurrence rate was assumed to be 200 cycles in the 40 year plant life. The operating pressure is 2,235 psi in the pipe. The safety shutdown earthquake (SSE) considered for the plant design has a peak ground acceleration (PGA) of 0.17 g. The time-history method used in the seismic stress analysis is described in detail in Ref. 5.

Duke Power Company calculated and then provided LLNL with piping stresses for Models 2 and 3. Dead load, pressure, and thermal expansion stresses were calculated by Duke using a method similar to that used by LLNL.

For Model 2, the heat-up and cool-down thermal transient with an occurrence rate of 200 cycles per plant life was considered in calculating thermal expansion stresses. The operating pressure is 715 psi. For Model 3, four thermal transients were considered significant. They are shut-down/cooldown (200 cycles), loss of load without immediate turbine or reactor trip (80 cycles), and inadvertant auxiliary spray (hot and cold, 10 cycles each). The operating pressure is 2,300 psi.

The seismic stress, however, was calculated by the response spectrum method described in detail in Ref. 5. Generally, conservatism built into the response spectrum method tends to over-estimate the seismic stress as

compared with the results obtained using the time-history analysis method. According to results shown in Ref. 5, the pipe stress calculated by the response spectrum method can be 2 to 8 times that resulting from the time history method. Therefore, the calculated seismic stresses for Models 2 and 3 were conservatively scaled down by a factor of 2.

Locations of all weld joints are indicated in Figs. 1, 2, and 3. Weld joints in each piping system were divided into several groups according to similarities in geometry, weld volume, and stress. In each group, a typical weld joint was selected to represent that group. Selection was based on the assumption that the stress at that weld joint being very close to the average stress among the group. To save calculational effort for the piping reliability analysis, the stress at every weld joint in the same group was assumed equal to that at the representative weld joint for that group. Model 2 serves as an example. This model has 17 weld joints numbered consecutively from the accumulator tank nozzle to the cold leg. The weld joints are divided into four groups. Group A has only one weld joint which is located at the accumulator tank nozzle. Group B includes two weld joints at the junction of the 10-in. pipe and the 6-in. pipe. Weld joint 10 was selected as the representative. Group C contains 13 weld joints at elbows with weld joint 16 chosen to represent the group. Group D also has only one weld joint, the cold leg nozzle joint. For Model 1 and Model 3, the grouping of weld joints was accomplished in a similar manner, and the results are summarized in Table 1.

2.1.3 Piping Reliability Analysis

We utilized the PRAISE computer code and a post-processor to conduct the piping reliability analysis. PRAISE takes piping stresses and other input data including the pipe geometry, the distribution of initial crack sizes, the pre-service and in-service inspection models, and the leak detection models to estimate pipe failure probabilities at pipe weld joints by applying a Monte Carlo method to simulate the life histories of a weld joint. Pipe failure is assumed to be caused by fatigue crack growth assuming that there exists an as-fabricated circumferential defect at the inner pipe surface in each weld. Failure is either a through-wall defect (leak) or a complete pipe severance (break). A complete pipe severance is reached if the state of internal forces and bending moments exceeds the ultimate capacity provided by the net pipe section. This failure criterion takes into consideration the interactive effect of axial force and bending moment. The post-processor appropriately combines the failure probabilities of pipe weld joints to obtain the failure probability of the entire piping system. Piping reliability is therefore numerically represented by the pipe failure probability in an inverse sense, i.e., higher reliability is indicated by a lower failure probability.

In the following, we discuss a few important features of the fracture mechanics model and the numerical simulation used in the current piping reliability analysis.

The initial crack distribution of crack depth is assumed to be exponential with a rate parameter of 4.065 in.^{-1} (or a mean crack depth

of 2.46 in.) in accordance with data reported by Marshall.^{6, 7} On the other hand, a truncated lognormal distribution of crack aspect ratio is assumed. The parameter analogous to the median aspect ratio, the parameter analogous to the shape factor, and the normalization constant are 1.336, 0.538, and 1.419, respectively. These values are derived from the assumption that one percent of cracks have a surface length greater than 10 times the depth.

With regard to the crack existence probability, the number of cracks in a body of weld volume is assumed to have a Poisson distribution. The rate of cracks per unit volume of weldment is taken to be 10^{-4} in.⁻³, a reasonable estimate in that it falls pretty much in the midrange of available data.

A Paris-type model^{6, 8} is used to describe the fatigue crack growth. The crack growth rate is adequately characterized by an empirical relationship following Bamford^{6, 8} and James.^{6, 9} The constant in the crack growth relationship assumes a lognormal distribution with a median value of 0.914×10^{-11} and a 90th percentile value of 0.350×10^{-10} . A value of 4 is given to the exponent in the crack growth relationship. The crack growth law has a threshold value of 4.6 ksi - in^{1/2} below which crack growth will not occur.

The PRAISE computer code employs a net-section critical-stress failure criterion to define a pipe break. The critical value of the net section stress is taken to be the flow stress, which is equal to the average value of the yield point stress and the ultimate stress. This criterion assumes that the maximum axial stress acts uniformly over the net section (or the uncracked section) at a pipe cross-section. The current study developed an improved failure criterion which accounts for both the axial force and the bending movement at the net section. This failure criterion states that a pipe break occurs if $M/M_L + (N/N_L)^2 > 1$. M and N are applied section moment and force, and M_L and N_L are the limit moment capacity and the limit force capacity of the net section. The flow stress which dictates moment and force capacities has a constant value of 44.9 ksi.

The PRAISE code considers only the heatup/cool-down thermal transient in calculating the fatigue crack growth attributed to the thermal expansion stress. This study developed an equation to compute an equivalent thermal expansion stress to express the combined effect of several thermal transients. A factor S is calculated from the following equation:

$$S^4 = (\sigma_{\max})_0^2 [(\sigma_{\max})_0 - (\sigma_{\min})_0]^2 + \sum_{i=1}^m (N_i/N_0) (\sigma_{\max})_i^2 [(\sigma_{\max})_0 - (\sigma_{\min})_0]^2$$

where $(\sigma_{\max})_0$ and $(\sigma_{\min})_0$ are the maximum and minimum stresses of the heatup/cool-down case; $(\sigma_{\max})_i$ and $(\sigma_{\min})_i$ are the maximum and minimum stresses of the *i*th thermal case; N_0 is the number of heatup/cool-down cycles; N_i is the number of cycles for the *i*th thermal case; and *m* is the total number of thermal cases in addition to the heatup/cool-down. The equivalent thermal expansion stress, $(\sigma_{TH})_{eg}$, is then expressed by:

$$(\sigma_{TH})_{eq} = 1/2 [((\sigma_{min})_0^2 + 4S^2)^{1/2} - (\sigma_{min})_0]$$

The PRAISE computer code uses the Monte Carlo simulation technique to estimate the pipe failure probability for a girth butt weld in the pipe. The failure probability is taken to be the ratio of the number of samples which have failed and the total sample size. A direct evaluation using the simple random sampling scheme is computationally inefficient because a very large number of random samples may be required before a statistically significant number of failures is obtained. The computer code employs a so-called stratified sampling scheme to enhance the accuracy and the computational efficiency of the Monte Carlo simulation. The basic idea is to partition the sample space into a set of mutually exclusive cells. A pre-determined number of samples is then selected from each cell. Within each cell, the individual crack dimensions are still selected according to the postulated initial crack size distribution. In this manner, the selected samples can be made more concentrated in the region where the pipe failure is more likely to occur and, hence, a considerable computational improvement can be achieved.

2.2 Reliability Assessment of Piping Redesign with Optimum Flexibility

Piping design, if desired, can be made more flexible by reducing the use of support devices through changes in design requirements, criteria, and practice. The PVRC Steering Committee on Piping Systems has been investigating possible changes with regard to NRC Regulatory Guides 1.122 and 1.61 dealing, respectively, with broadening floor response spectra and damping values for piping systems. Either of the changes has the effect of reducing calculated piping responses due to seismic loading and may potentially lead to a piping redesign that requires fewer supports to satisfy ASME code requirements.

This assessment determines a piping redesign with optimum or near--optimum piping flexibility, i.e., the least number of supports required. It also determines and compares piping reliabilities related, respectively, to the original design and the redesign.

2.2.1 Piping Models

We selected the 14-in. pressurizer surge line and a portion of the auxiliary feedwater (AFW) system, both from Plant B, for the reliability assessment of piping redesign with optimum or near-optimum piping flexibility. The 14-in. surge line and its comparable analytical model (Model 1) have been discussed in 2.1.1. The portion of the AFW system consists of a 3-in. pipe run extending from the containment wall and joining a 16-in. pipe line which runs between the steam generator and the containment wall. The analytical model for the portion of AFW system is referred to as Model 4, as shown by Fig. 4. This model has 15 vertical hangers, 10 lateral rigid supports, and two snubbers. The 16-in. pipe has an outside diameter of 16 in. and a thickness of 1.219 in. The 3-in. pipe has an outside diameter of 3.5 in. and a thickness of 0.438 in. The material is A1-6-GRB carbon steel.

2.2.2 Changes in Design Requirements for Piping Redesign

Certain changes in design requirements were adopted to allow a piping redesign with optimum flexibility for each of the selected piping systems. These changes are currently being investigated by the PVRC Technical and Steering Committees for Piping Systems with respect to the NRC Regulatory Guides 1.61 and 1.122 (RG 1.61 and RG 1.122). RG 1.61 specifies damping values for seismic design of nuclear power plants, whereas RG 1.122 defines floor design response spectra for seismic design of floor-supported equipment or components.

The damping values specified by RG 1.61 and the PVRC proposed damping values are presented by Fig. 5. It is noted that the PVRC proposed damping value is substantially higher than that currently allowed by RG 1.61 in the lower frequency range.

Meanwhile, the PVRC Technical Committee proposed an alternative procedure to count for the uncertainty in calculated frequencies of the supporting structure. RG 1.122 suggested a broadened floor response spectrum curve, while the alternative procedure recommends the unbroadened response spectrum curve to be shifted in a certain manner (see Fig. 6).

Either of the changes proposed by the PVRC has the effect of reducing calculated seismic responses for a piping system; hence, allowing a more flexible piping design without violating ASME code requirements.

2.2.3 Optimum Flexibility Piping Redesign

An iterative procedure was adopted in order to arrive at a piping redesign with optimum or near optimum flexibility for each of the selected piping systems. During the iterative procedure, we merely considered several different combinations of pipe supports to be removed from the existing design without relocating the remaining pipe supports. This limited optimization procedure was adopted because a rigorous optimization was judged to be too time consuming for this assessment.

We performed a stress analysis and an ASME code calculation for each of the pipe redesign during the iterative procedure. This procedure finally resulted in a piping redesign which not only satisfies ASME code allowables, but also has the least number of pipe supports.

2.2.4 Piping Reliability Analysis

The method used in the piping reliability analysis for both the original design and the redesign is the same as that described in 2.1.3.

3. RESULTS AND DISCUSSIONS

3.1 Confirmatory Piping Reliability Assessment

Various load cases were considered for each piping model. A load case corresponds to a piping design with a specific support arrangement. Load cases for the three piping models are described by Tables 2, 3 and 4. Load Cases 1, 2 and 3 represent piping designs with increasing flexibility. Load Cases 4, 5, etc. correspond to piping designs with selected snubbers either removed or assumed to be locked in. Results of stress analyses were summarized in Table 5, 6, and 7, respectively, for Models 1, 2, and 3.

As we have stated above, Load Cases LC1, LC2, and LC3 were selected in a fashion such that the piping flexibility was increased or the number of supports was gradually decreased. The purpose of their selection was to observe the effect on piping reliability of increased piping flexibility. On the other hand, Load Cases LC4, LC5, etc. were analyzed in order to observe the effect of snubber failure with regard to piping reliability. From Tables 5, 6, and 7, we made the following observations:

- (1) Increasing piping flexibility (or removing pipe supports) in general tends to reduce the thermal expansion stress but increase the seismic stress.
- (2) When snubbers fail in a "free" mode (equivalent to a situation where snubbers are removed), the failure does not affect the thermal expansion stress but the seismic stress will be increased.
- (3) When snubbers fail in a "locked" mode, the failure often causes an increase in the thermal expansion stress although the seismic stress remains unchanged.

Results of the piping reliability analysis for Load Cases LC1, LC2, and LC3 as indicated by Tables 8, 9, and 10 suggested that the piping reliability (or the pipe failure probability) is not very sensitive to the change in piping flexibility for the piping systems we have studied. Furthermore, pipe failure probabilities are generally small, i.e., approximately 10^{-9} for "break" and 10^{-6} for "leak". This can be viewed as an indication that piping stresses appear to be very well controlled under the current piping design practice. This insensitivity is particularly true for leak probabilities where the effect of change in piping flexibility appears to be almost negligible. The reason could be twofold: (1) the change in piping flexibility usually fails to cause sufficient change in the thermal expansion stress to have a pronounced impact on the leak probability; and (2) the seismic stress has been known to have little influence on the leak probability as indicated in Ref. 6. Therefore, from this point on, the piping reliability will be discussed only in accordance with the pipe break probability.

For Model 1, we have seen improved piping reliability with increased piping flexibility. This is usually true when the thermal stress is relatively high in the pipe. For Model 2, the piping reliability first increases with increased piping flexibility, then starts to decline as the piping design becomes excessively flexible. Results for Model 3 indicated that the piping reliability tends to decrease with increased flexibility since the thermal expansion stress is very low in the pipe. In any event, when there is a reduction in piping reliability, the reduction can be considered to be only moderate.

An increase in piping reliability for flexible piping design is generally attributed to relaxation in the thermal expansion stress for flexible piping although the seismic stress may be increased by piping flexibility. The thermal stress is usually caused by the 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, the seismic stress is caused by an earthquake which is a natural phenomenon with low probability of occurrence. Therefore, the contribution to pipe failure due to seismic loads is of secondary importance when the event occurrence rate of an earthquake is considered in the piping reliability analysis.

Removing snubbers to increase piping flexibility will increase the seismic stress but will not affect the thermal stress. If snubbers were perfect, removal of snubbers would increase the seismic stress which would then cause a reduction in piping reliability. Even so, the reduction in piping reliability is generally quite moderate (see, for instance, results for LC1 and LC6 in Table 5). In real situations, snubbers are known to malfunction with considerably high frequency. In other words, snubbers generally fail frequently either in a "locked" mode or a "free" mode. In either case, the piping reliability will be reduced. (See results for LC4, LC5 etc. in Tables 5, 6, and 7.)

The Load Case LC1* appearing in Tables 5, 6, and 7 is the same as LC1, which represents the existing piping design, with the exception that the pipe failure probability was computed for LC1* with the consideration that a snubber may fail either in a "free" mode or a "locked" mode. We have assumed, arbitrarily but realistically, a 10% failure probability for each of the snubber failure modes. A more realistic snubber failure rate will be established in our future study. Specifically, the pipe failure probability associated with Load Case LC1* (P_1^*) for piping Model 1 is computed by

$$P_1^* = 0.66 P_1 + 0.08 (P_4 + P_5 + P_7 + P_8) + 0.01 (P_6 + P_9),$$

where P_i ($i=1, 2, \dots, 9$) denotes the pipe failure probability associated with the Load Case i . Likewise, for Models 2 and 3,

$$P_1^* = 0.8 P_1 + 0.1 (P_4 + P_5).$$

We have demonstrated for Model 2 that the piping reliability is

actually improved by removing a snubber as indicated by the results for LC1* and LCS. Load Case LCS is the piping design with the snubber removed. In this case, the result was attributed to the fact that the thermal expansion stress for LC5, as clearly indicated in Table 6, was increased significantly as the snubber failed in a "locked" mode as was assumed from Load Case LC5. For Models 2 and 3, the piping reliability was practically not affected by removing snubbers from the existing design. In this case, the result led us to question the necessity of adding the snubber (or snubbers) in the first place. Nevertheless, this practice has been quite common in designing nuclear power plant piping systems.

3.2 Piping Redesigns With Optimum Flexibility

We adopted an iterative procedure to arrive at piping redesigns for two existing piping systems: the 14-in. pressurizer surge line (Model 1) and a portion of the AFW system (Model 2), both from Plant B, which is a pressurized-water-reactor plant. We performed a stress analysis and an ASME Code evaluation for each of the intermediate piping designs considered during the iterative process. The stress analysis employed the response spectrum method and incorporated the changes proposed by the PVRC Technical and Steering Committees for piping systems with respect to RG 1.61 and RG 1.122. Either of the changes has the effect of reducing calculated seismic responses while retaining sufficient margins of conservatism for a piping system as demonstrated in Ref. 5 and illustrated by Figs. 7 and 8. The iterative procedure finally resulted in piping redesigns which not only satisfy ASME code allowables but also have the least number of pipe supports. In other words, the adoption of the PVRC proposed changes has allowed the elimination of a significant number of seismic supports from the existing piping designs without violating ASME code requirements. As a result, seven out of 10 lateral seismic supports and both snubbers were eliminated from the existing AFW model, whereas all seismic supports (one lateral support and two snubbers) were eliminated from the pressurizer surge line model. Figure 9 clearly illustrates that the calculated piping stresses in the flexible redesign of the AFW model meet ASME code allowables only after the PVRC proposed changes to RG 1.61 and RG 1.122 have been implemented.

We eventually performed a piping reliability analysis for each of the piping systems to determine and compare piping reliabilities related, respectively, to the existing design and the optimum redesign. The results are illustrated in Table 11.

It is noted that the probability of snubber malfunction was incorporated as we computed pipe break probabilities for the original designs. Results shown by Table 11 indicate that the more flexible redesigns are capable of exhibiting reliability levels equal to or higher than the original stiffer designs.

4. CONCLUSIONS

Based on results of the current study, our conclusions can be summarized as follows:

- The change in piping reliability is not very sensitive to the change in piping flexibility for the cases we have studied. Pipe failure probabilities are generally small, i.e., approximately 10^{-9} for "break" and 10^{-6} for "leak". This can be viewed as an indication that piping stresses appear to be very well controlled under current piping design practice. In many cases, the piping reliability actually improves with increased piping flexibility. This is usually true when the thermal stress in the pipe is relatively high. In other cases, the piping reliability tends to decrease with increased flexibility when the thermal stress is very low or when the piping system becomes excessively flexible. In any event, the reduction in piping reliability can be considered to be only moderate.
- Removing snubbers to increase piping flexibility will increase the seismic stress but will not affect the thermal stress. If snubbers were perfect, removal of snubbers would increase the seismic stress which would cause reduction in piping reliability. Even so, the reduction in piping reliability is generally quite moderate. In real situations, snubbers have low reliability. That is, snubbers frequently fail either in a "locked" mode or a "free" mode. When snubber failure is "locked", it will usually introduce excessive thermal expansion stress in the pipe. If failure is "free", the pipe will experience higher seismic stress than that for which it was designed. In either case, the piping reliability will be reduced. The degree of reduction in piping reliability strongly depends on the amount the thermal expansion stress is increased. In severe cases, it can create serious safety concerns. We have demonstrated that the piping reliability can actually be improved by removing snubbers from the existing design. This is generally true for piping systems with relatively high thermal stress.
- 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.
- The design practice has been found to play an important role in affecting the piping reliability. The piping reliability usually can be improved by removing seismic supports for piping systems subject to higher thermal expansion stress in the initial design. In this case, the failure of snubbers in the locked mode can cause serious degradation to the piping system. On the other hand, we have discovered that

unnecessary snubbers were often added during the piping design procedure, even though the thermal stress was quite low in the pipe. Clearly, a more systematic assessment of the role design practice plays in terms of piping reliability is needed.

- 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. Furthermore, flexible piping redesigns are capable of exhibiting reliability levels equal to or higher than the original stiffer designs.
- Although we have demonstrated that piping systems can be made more reliable by adopting flexible piping designs based on the piping reliability analysis conducted in this study, we do caution that changes adopted in the piping design procedure to increase the piping flexibility 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.
- In addition to changes proposed by the PVRC, there are certainly other areas in piping design requirements, criteria, and procedures where changes can be made to allow for more flexible piping design. As we explore these areas in our continued study we caution that, if these changes are evaluated individually and hastily put together, we may easily fall into a dangerous situation where the reliability or safety of a piping design may be greatly jeopardized. Therefore, in considering any future changes in piping design requirements, criteria, and procedures, the overall or integrative effect on the piping reliability as well as the safety margin due to the combination of these changes ought to be carefully evaluated.
- Since on-line components (such as pumps and valves) and embedments are important parts of a piping system, the effects of reducing pipe support devices on the reliability of components and embedments should also be carefully investigated. Evaluating these effects will be one of our major tasks in the remaining study.
- 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 will examine the feasibility of eliminating pipe whip restraints based on its impact on piping reliability.

5. REFERENCES

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Table 1. Grouping of weld joints.

Piping Model	Weld Joint Group	Weld Joints in Group
Model 1	A	1*, 2
	B	3, 4*
	C	5, 6*
	D	7, 8*
	E	9*
Model 2	A	1*
	B	10*, 11
	C	2, 3, 4, 5, 6, 7, 8, 9, 12, 13, 14, 15, 16*
	D	17*
Model 3	A	1*, 2
	B	3, 4, 5*
	C	6, 7, 8*
	D	9*, 10, 11, 12
	E	13, 14, 15, 16, 17, 18, 19*
	F	20*, 21, 22, 23, 24

*This weld joint was selected to represent the group.

Table 2. Load cases analyzed for piping model 1.

Load Case 1 (LC1) - Existing Design (all seismic supports attached)
Load Case 2 (LC2) - All seismic supports except snubbers removed
Load Case 3 (LC3) - All seismic supports (including snubbers) removed
Load Case 4 (LC4) - Given snubber A in "free" mode
Load Case 5 (LC5) - Given snubber B in "free" mode
Load Case 6 (LC6) - Given snubbers A and B in "free" mode
Load Case 7 (LC7) - Given snubber A in "locked" mode
Load Case 8 (LC8) - Given snubber B in "locked" mode
Load Case 9 (LC9) - Given snubbers A and B in "locked" mode

Table 3. Load cases analyzed for piping model 2.

Load Case 1 (LC1) - Existing design (all seismic supports attached)
Load Case 2 (LC2) - One lateral support (D) removed
Load Case 3 (LC3) - Four lateral supports (D, G, H, I) removed
Load Case 4 (LC4) - Given the snubber in "free" mode
Load Case 5 (LC5) - Given the snubber in "locked" mode

Table 4. Load cases analyzed for piping model 3.

Load Case 1 (LC1) - Existing design (6 laterals, 10 snubbers)
 Load Case 2 (LC2) - Supports E, F, J, L, and P removed
 Load Case 3 (LC3) - All laterals and snubbers K, M, and O removed
 Load Case 4 (LC4) - Snubber I in "free" mode
 Load Case 5 (LC5) - Snubber I in "locked" mode

Table 5. Summary of stresses for piping model 1.

Load Case	Thermal Expansion Stress by Weld Joint Group (ksi)					Seismic (OBE) Stress by Weld Joint Group (ksi)				
	A	B	C	D	E	A	B	C	D	E
LC1	2.720	12.560	4.361	10.728	16.466	0.301	0.326	0.207	0.639	0.010
LC2	3.579	5.766	1.859	3.480	4.941	0.295	0.357	0.257	1.003	1.523
LC3	3.579	5.766	1.859	3.480	4.941	0.439	0.332	0.301	1.085	1.636
LC4	2.720	12.560	4.361	10.728	16.466	0.389	0.332	0.232	0.752	1.060
LC5	2.720	12.560	4.361	10.728	16.466	0.385	0.439	0.270	0.878	1.316
LC6	2.720	12.560	4.361	10.728	16.466	0.451	0.458	0.257	0.790	1.135
LC7	6.471	15.203	4.799	8.309	10.716	0.301	0.326	0.207	0.639	1.010
LC8	2.398	15.199	2.549	10.132	20.018	0.301	0.326	0.207	0.639	1.010
LC9	6.685	17.947	2.550	6.843	15.268	0.301	0.326	0.207	0.639	1.010

Note: LC1 - Existing Design (all seismic supports attached)
 LC2 - All seismic supports except snubbers removed
 LC3 - All seismic supports (including snubbers) removed
 LC4 - Given snubber A in "free" mode
 LC5 - Given snubber B in "free" mode
 LC6 - Given snubbers A and B in "free" mode
 LC7 - Given snubber A in "locked" mode
 LC8 - Given Snubber B in "locked" mode
 LC9 - Given Snubbers A and B in "locked" mode

Table 6. Summary of stresses for piping model 2.

Load Case	Thermal Expansion Stress by Weld Joint Group (ksi)				Seismic (OBE) Stress by Weld Joint Group (ksi)			
	A	B	C	D	A	B	C	D
LC1	0.861	6.156	2.971	4.153	0.355	0.743	0.477	0.810
LC2	2.339	4.592	1.835	3.432	0.926	0.695	0.456	0.838
LC3	7.018	2.604	1.723	2.096	62.910	4.315	6.147	8.212
LC4	0.861	6.156	2.971	4.153	0.370	0.694	2.082	3.470
LC5	2.831	30.117	26.070	60.846	0.355	0.743	0.477	0.810

Note: LC1 - Existing design (all seismic supports attached)
 LC2 - One lateral support (D) removed
 LC3 - Four lateral supports (D, G, H, I) removed
 LC4 - Given the snubber in "free" mode
 LC5 - Given the snubber in "locked" mode

Table 7. Summary of stresses for piping model 3.

Load Case	Thermal Expansion Stress by Weld Joint Group (ksi)						Seismic (OBE) Stress by Weld Joint Group (ksi)					
	A	B	C	D	E	F	A	B	C	D	E	F
LC1	2.821	0.775	1.865	0.773	0.773	0.637	0.688	0.525	0.670	0.234	0.119	0.156
LC2	2.404	1.833	1.139	0.499	0.130	0.148	0.985	1.143	2.062	0.706	3.039	2.396
LC3	2.619	0.919	1.444	0.566	0.285	0.120	7.640	7.600	6.558	2.298	3.629	3.865
LC4	2.821	0.775	1.865	0.773	0.773	0.637	0.662	0.469	0.703	0.244	0.362	0.417
LC5	4.393	1.321	2.693	1.123	1.305	1.204	0.689	0.526	0.672	0.235	0.118	0.156

Note: LC1 - Existing design (6 laterals, 10 snubbers)
 LC2 - Supports E, F, J, L, P removed
 LC3 - All laterals and snubbers K, M, O removed
 LC4 - Snubber I in "free" mode
 LC5 - Snubber I in "locked" mode

Table 8. Summary of pipe failure probabilities for piping model 1.

Load Case	Break	Leak
LC1	0.102×10^{-8}	0.372×10^{-5}
LC2	0.578×10^{-9}	0.175×10^{-5}
LC3	0.578×10^{-9}	0.175×10^{-5}
LC4	0.108×10^{-8}	0.373×10^{-5}
LC5	0.109×10^{-8}	0.373×10^{-5}
LC6	0.109×10^{-8}	0.373×10^{-5}
LC7	0.199×10^{-8}	0.466×10^{-5}
LC8	0.182×10^{-8}	0.512×10^{-5}
LC9	0.337×10^{-8}	0.633×10^{-5}
LC1*	0.120×10^{-8}	---
LCS(=LC6)	0.109×10^{-8}	---

- Note:
- LC1 - Existing Design (all seismic supports attached)
 - LC2 - All seismic supports except snubbers removed
 - LC3 - All seismic supports (including snubbers) removed
 - LC4 - Given snubber A in "free" mode
 - LC5 - Given snubber B in "free" mode
 - LC6 - Given snubbers A and B in "free" mode
 - LC7 - Given snubber A in "locked" mode
 - LC8 - Given snubber B in "locked" mode
 - LC9 - Given snubbers A and B in "locked" mode
 - LC1* - Same as LC1 but subject to snubber failure probability
 - LCS - Same as LC1 but with snubbers removed

Table 9. Summary of pipe failure probabilities for piping model 2.

Load Case	Break	Leak
LC1	1.143×10^{-9}	6.691×10^{-6}
LC2	9.514×10^{-10}	4.523×10^{-6}
LC3	6.645×10^{-8}	6.396×10^{-6}
LC4	1.255×10^{-9}	6.700×10^{-6}
LC5	2.731×10^{-7}	7.864×10^{-6}
LC1*	2.837×10^{-8}	---
LCS(=LC4)	1.255×10^{-9}	---

- Note:
- LC1 - Existing design (all seismic supports attached)
 - LC2 - One lateral support (D) removed
 - LC3 - Four lateral supports (D, G, H, I) removed
 - LC4 - Given the snubber in "free" mode
 - LC5 - Given the snubber in "locked" mode
 - LC1* - Same as LC1 but subject to snubber failure probability
 - LCS - Same as LC1 but with the snubber removed

Table 10. Summary of pipe failure probabilities for piping model 3.

Load Case	Break	Leak
LC1	2.833×10^{-10}	3.150×10^{-7}
LC2	3.352×10^{-10}	3.019×10^{-7}
LC3	9.996×10^{-10}	3.084×10^{-7}
LC4	2.839×10^{-10}	3.150×10^{-7}
LC5	3.544×10^{-10}	3.526×10^{-7}
LC1*	2.905×10^{-10}	---
LCS(=LC4)	2.839×10^{-10}	---

- Note
- LC1 - Existing design (6 laterals, 10 snubbers)
 - LC2 - Supports E, F, J, L, and P removed
 - LC3 - All laterals and snubbers K, M, and O removed
 - LC4 - Snubber I in "free" mode
 - LC5 - Snubber I in "locked" mode
 - LC1* - Same as LC1 but subject to snubber failure probability
 - LCS - Same as LC1 but with snubber I removed

Table 11. Comparison of pipe break probabilities.

Piping Model	Original Design	Optimum Redesign
Model 1: Surge Line	0.120×10^{-8}	0.578×10^{-9}
Model 4: AFW Line	0.327×10^{12}	0.616×10^{-12}

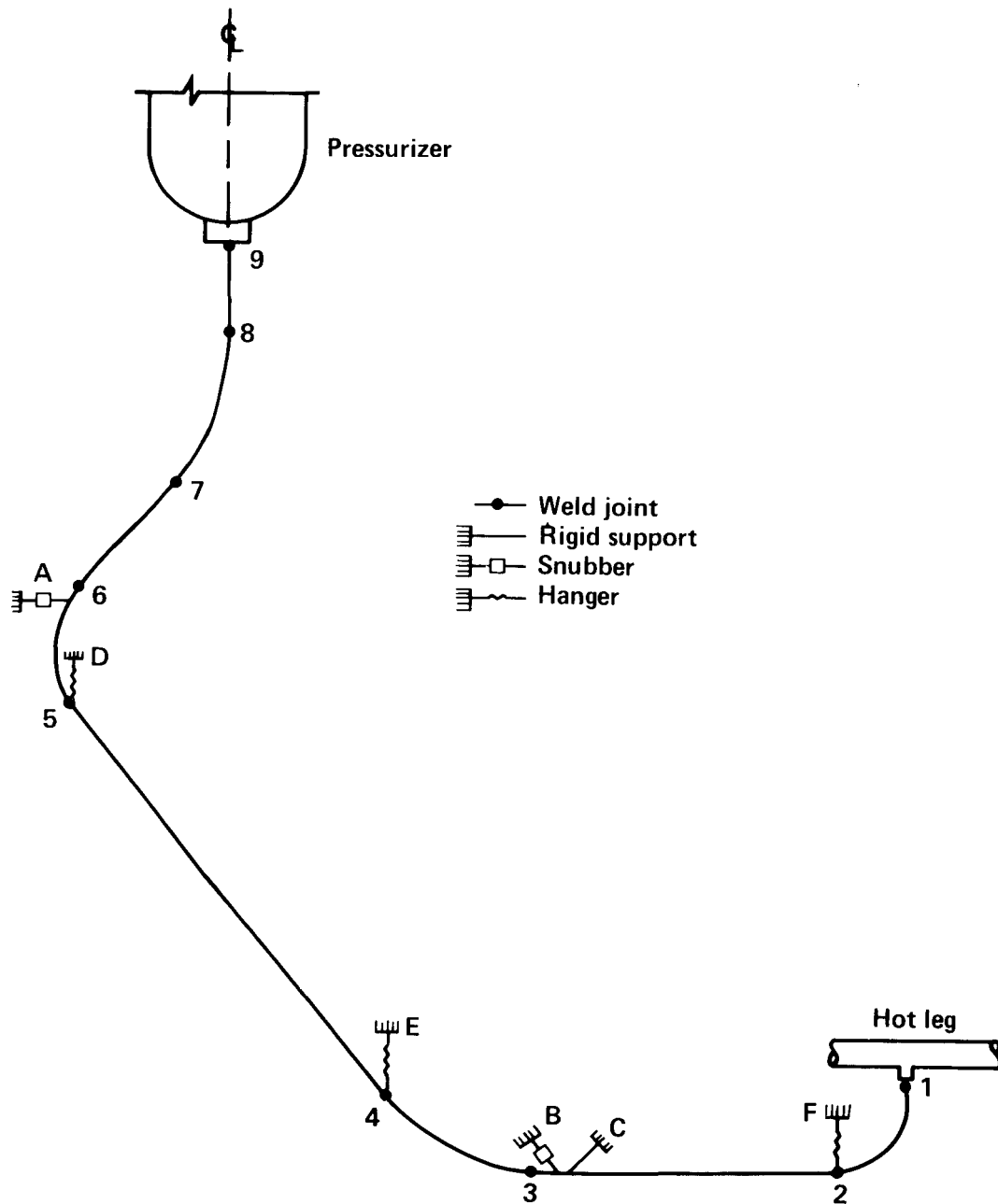


Figure 1. Pressurizer surge line from Plant A.

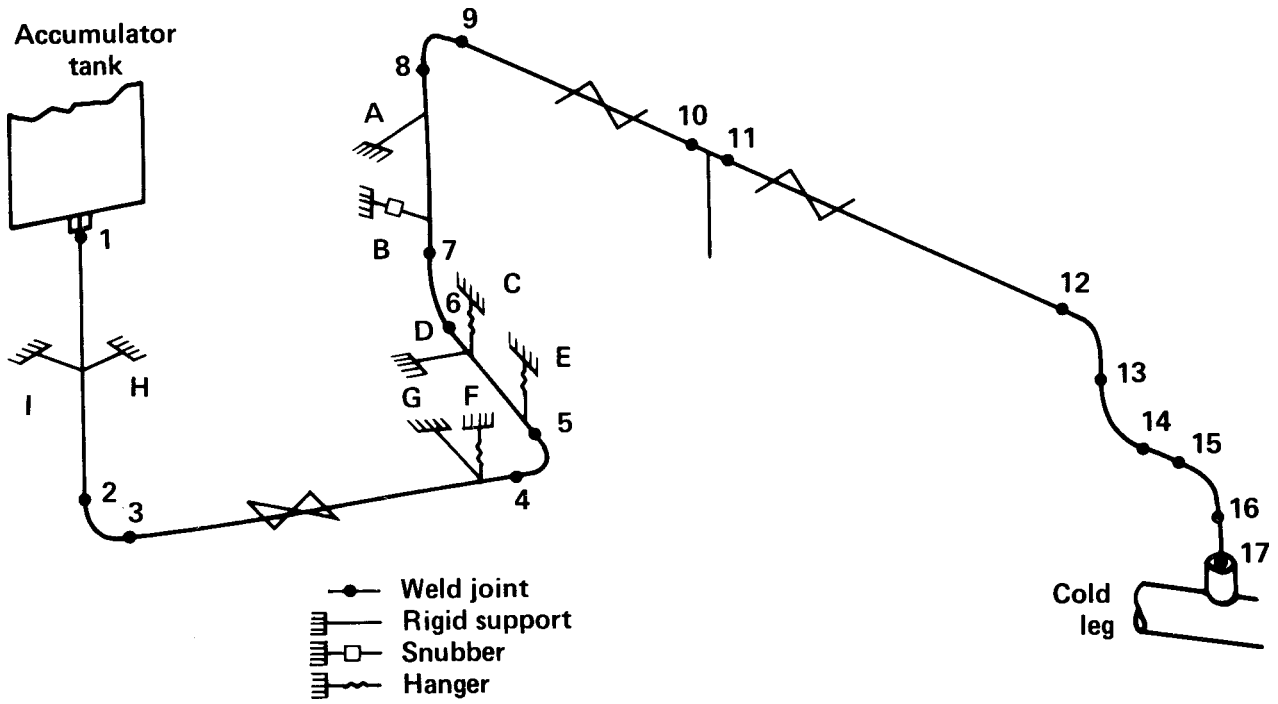


Figure 2. Safety injection line from Plant B.

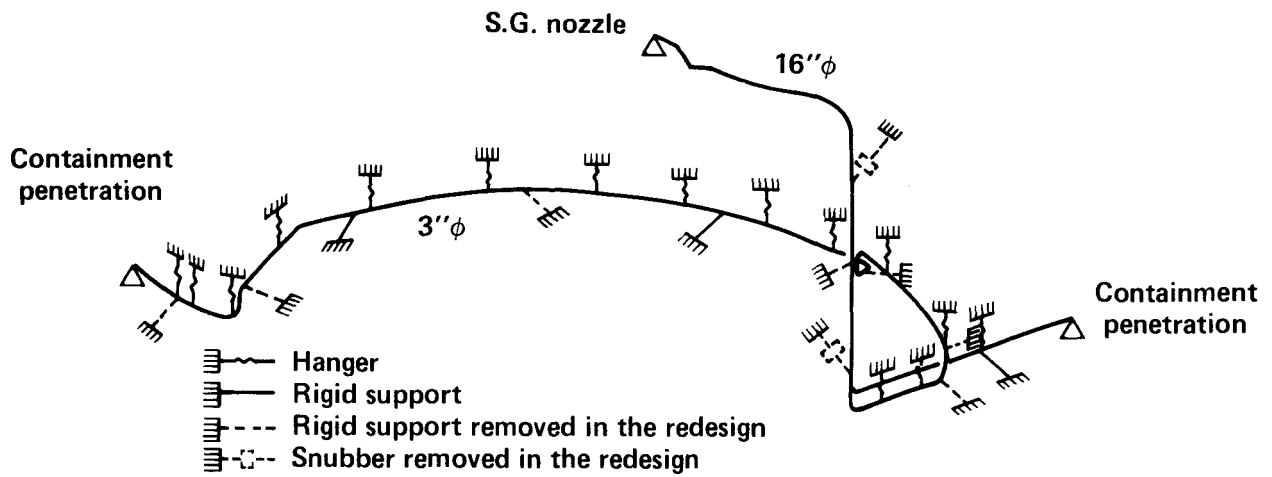


Figure 4. AFW line inside containment from Plant A.

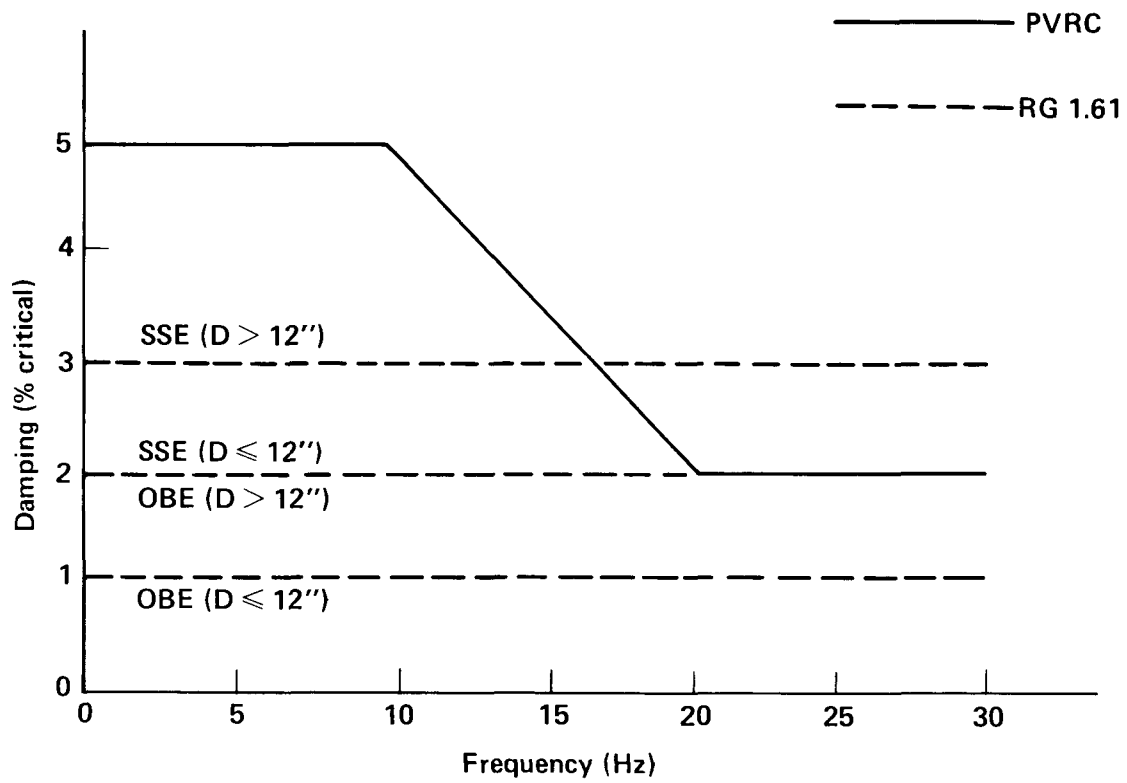
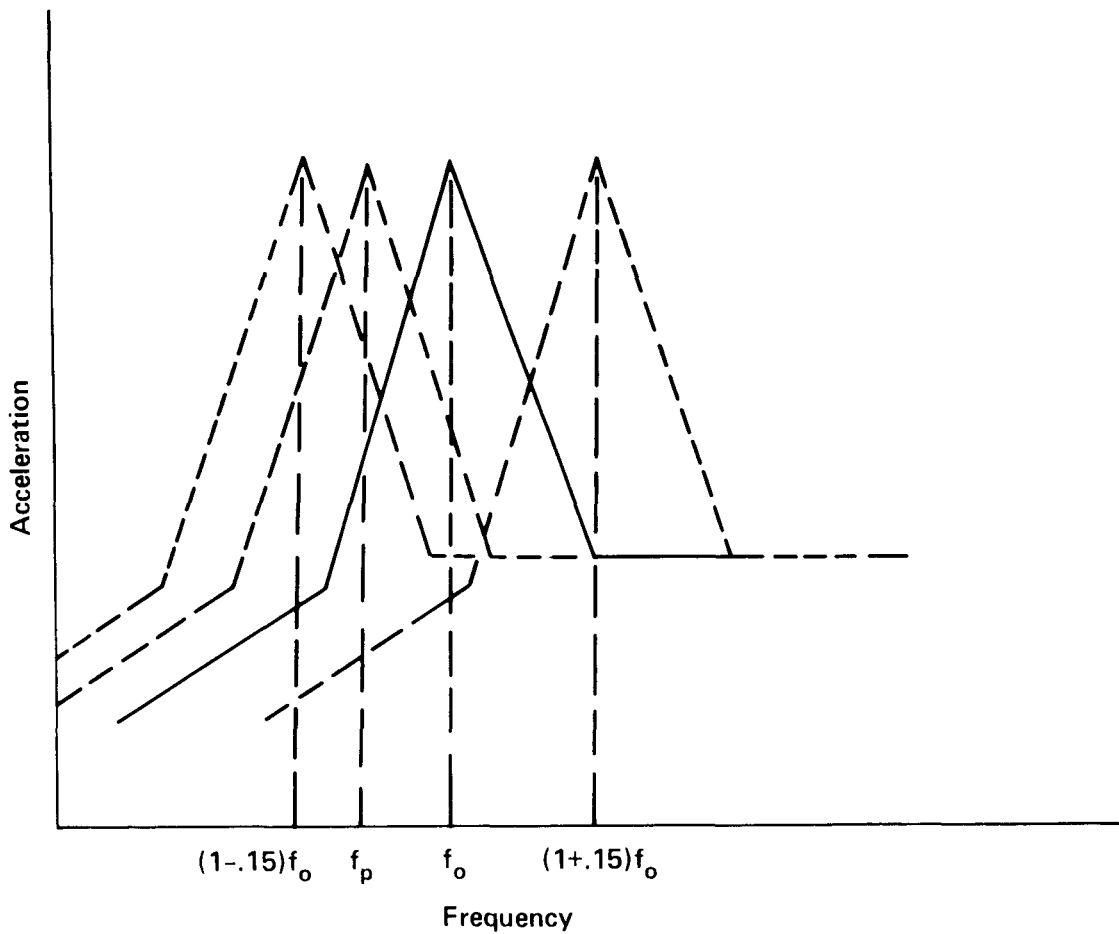


Figure 5. PVRC proposed damping vs RG 1.61 damping.



PVRC Proposed Procedure:

1. Identify piping modes and frequencies lying in the $\pm 15\%$ range of the peak frequency of the unbroadened spectrum, f_0 .
2. Shift the spectrum to match the peak at the following frequencies: f_0 , $(1 \pm .15)f_0$, and each of the piping frequencies, f_p .
3. Perform response spectrum analysis for each shifted spectrum and use the maximum response calculated.

Figure 6. PVRC proposed change to RG 1.122.

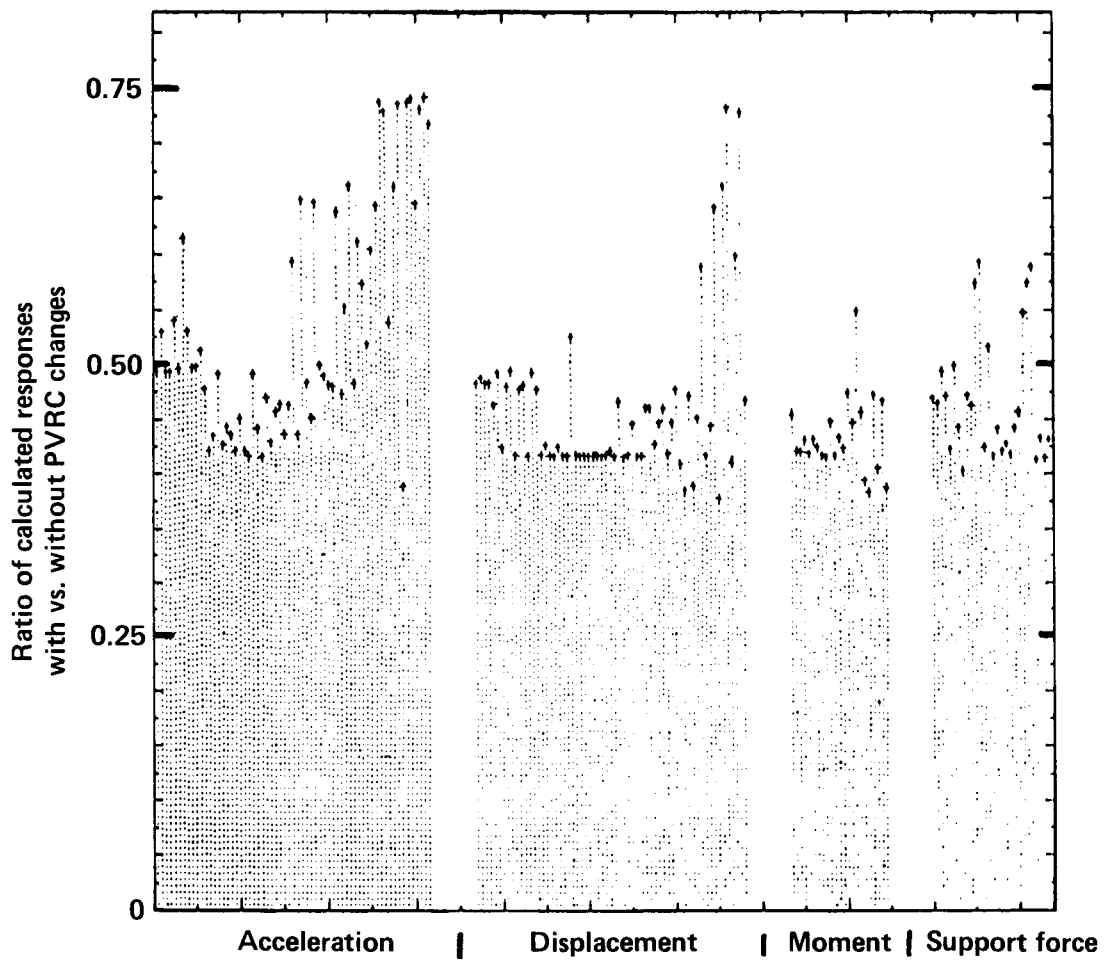


Figure 7. Comparison of calculated responses (with and without PVRC proposed changes).

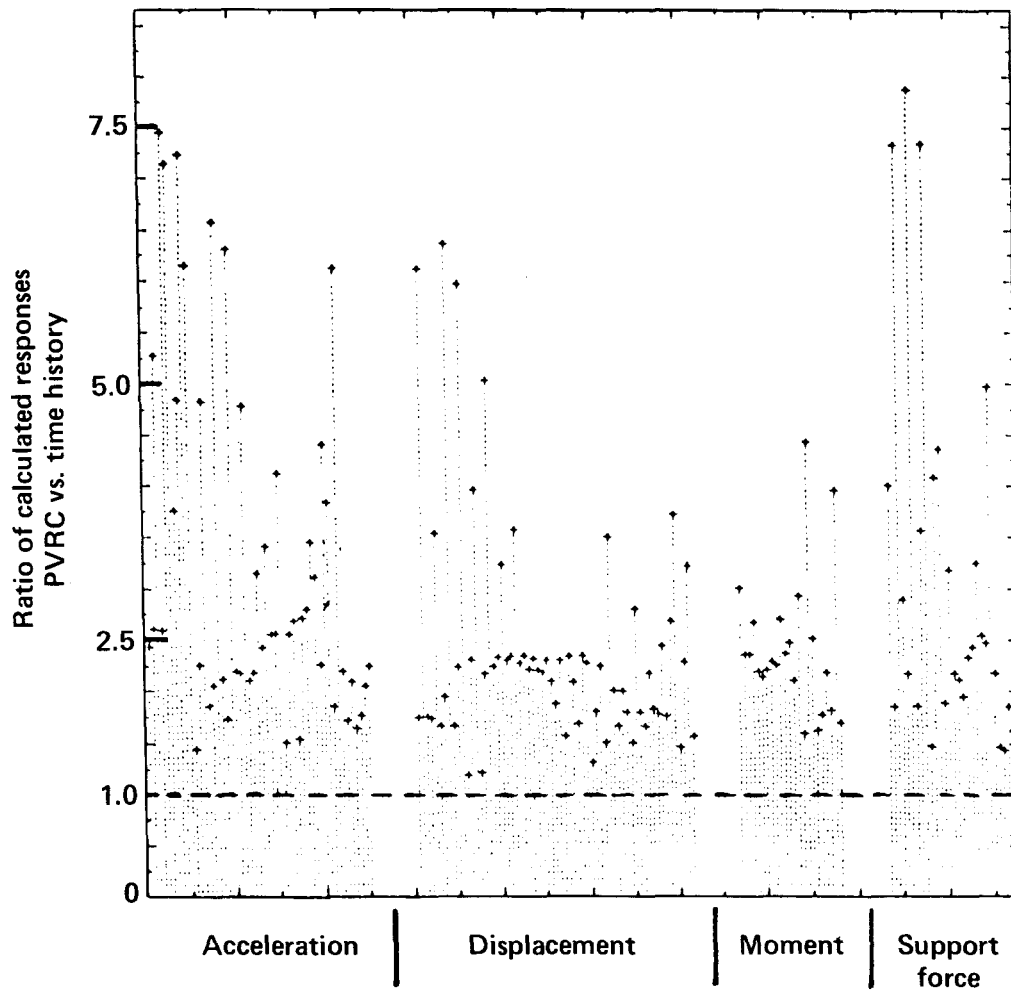


Figure 8. Comparison of calculated responses (PVRC changes vs time-history analysis).

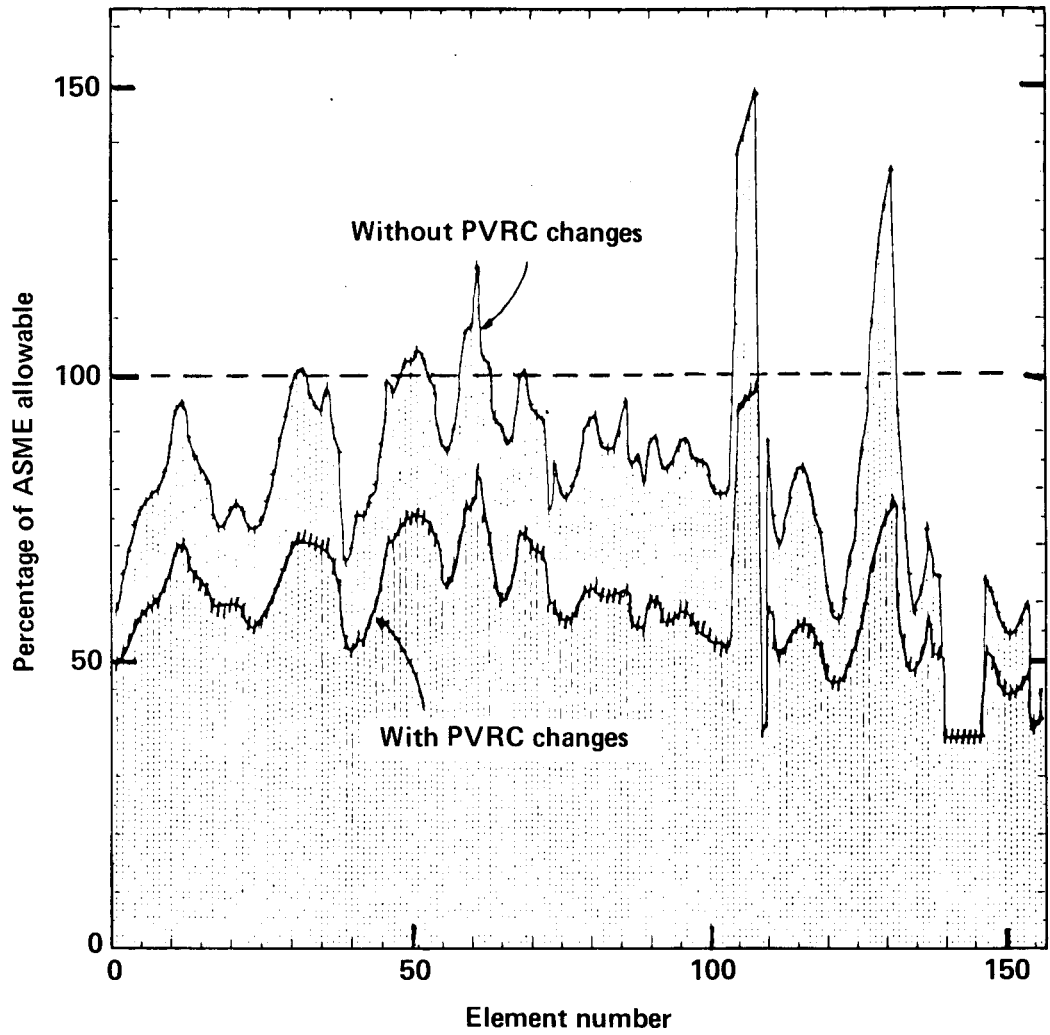


Figure 9. Summary of ASME code evaluation.

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