Criteria for Protection Against the Consequences of Pipe Rupture

P.C. Strange, R.D. Wheaton
EDS Nuclear Inc.,
220 Montgomery Street, San Francisco, California 94104, U.S.A.

ABSTRACT

The probability of a pipe rupture in a nuclear power plant is considered significant enough that the dynamic effects of high-energy piping failures must be accounted for. Pipe rupture-related work represents a major financial and scheduling factor for new plants; its effects could be even more burdensome for existing plants which must be upgraded to current standards. This paper suggests an approach to determining rupture restraint requirements that could increase the level of protection afforded and reduce the associated costs.

The current regulatory approach to the problem mandates that protection will be provided only against a discrete number of the most probable ruptures. The degree of protection required in these cases is very high and, as a result, the rupture restraints used in this approach are so massive and costly that they cannot be provided for all possible rupture locations. As a result, many potential targets are essentially unprotected.

It is the contention of the authors that a significantly greater level of overall protection could be achieved by the adoption of a more coherent and comprehensive approach to the probem. The revised approach would entail the use of more reasonable (lower) design loads and would thus allow more rupture restraints, and more effective rupture restraints, to be distributed throughout the plant.

The suggested approach is derived by simultaneously considering the probabilities associated with four distinct parameters: rupture location, rupture type and orientation, pipe whip force magnitude, and performance level of the restraint. It is shown, through a hypothetical example, that the overall level of risk can be reduced by eliminating a portion of the conservatism in load definition and restraint design, and by introducing ring-type restraints at more locations. Two factors dominate the results: first, that reducing the design loads (and, hence, restraint size) has little effect on overall risk; and, second, that a significant portion of the risk is associated with break locations other than those presently considered. Smaller, more numerous restraints, therefore, result in a more balanced design and a safer plant.

1. Introduction

A nuclear power plant contains many high-energy pipelines within a confined and congested area. Despite their being designed to strict criteria and constructed to close tolerances, there exists a finite probability that a pipe will rupture. The large release of energy resulting from such a rupture could cause damage, which might prevent the plant from shutting down safely.

As the probability of a pipe rupture is considered to be significant, federal regulations stipulate that the dynamic effects of postulated failures be accounted-for in a nuclear plant design.

Pipe rupture-related work represents a major financial and scheduling control on the design and construction of a new plant. Its effect could be even more burdensome for existing plants which must be upgraded to current standards. Many factors serve to amplify the difficulty of furnishing the required protection against the consequences of pipe rupture. Paramount among these is the large design force which must be considered when physical barriers are used.

In this paper, it is argued that the magnitude of these design forces, which is dictated by the current regulatory licensing position, is too high, and that a greater level of protection could be obtained were it to be reduced.

2. Philosophy of Pipe Rupture Protection

There is virtually an infinite number of possible rupture locations and rupture types. Each has a small, but finite, probability of occurrence, and for each possible rupture there is a finite probability that the whipping pipe or high-energy fluid jet will strike a component necessary for safe plant shutdown. Further, there is a finite probability that this component will be damaged by the interaction, and that this will cause a significant loss in plant safety.

Regulatory Guides now stress that physical distancing of vulnerable components from potential ruptures should be adopted as the principal mode of protection. This counsel, while commendable, is often impractical, particularly in existing plants. Thus, physical barriers must be built to prevent unacceptable interactions.

A rigorous and complete approach to the design of these barriers would involve the estimation of the probability of ruptures at all locations, the determination of the net probability of unacceptable consequences due to each rupture, and the provision of barriers or restraints to reduce the overall risk to an acceptable level.

Such an approach is theoretically possible but largely impracticable, due to the complexity of the problem. It is doubtful that the input parameters could be defined with sufficient confidence at present to justify the approach. Thus, a simplified method is currently used wherein only the most probable ruptures are addressed. This approach affords a high degree of protection for a discrete number of unacceptable targets. Various requirements have been established in an attempt to ensure that this approach will furnish integral and effective protection.

It must be emphasized that complete protection against the consequences of pipe rupture is neither sought nor attained; rather, the objective is to reduce the overall risk to an acceptable level. While quantification of this risk may not be possible, further reduction by provision of more restraints would involve great increases in cost due to the restraint size and the limited space available for support structure. It is unlikely that the

increased benefit could match this increased cost. It is the contention of the authors, however, that significant increase in benefit (i.e. protection) can be obtained without increase in cost, through fundamental changes in the current regulatory criteria. These changes would allow more restraints to be built to significantly lower design loads.

3. Level of Protection Provided by Pipe Rupture Restraints

Consider the simple system shown in Figure 1, consisting of a pipe and two 'targets' or vulnerable components. This is a microcosm of the complex geometry present within a nuclear power plant. We are concerned with the probability that a pipe rupture will cause damage to either or both of the targets. As a gross, but not unreasonable, approximation, it is assumed that the problem can be reduced to the consideration of four parameters: the probability of a rupture at each location on the pipe, the probable type or orientation of rupture at each location, the probable magnitude of the resulting unbalanced forces on the pipe, and the probability that the target will be struck.

3.1 Probability of Rupture

Pipe ruptures, as with all engineering failures, can be divided into two types: those which are induced by mechanisms considered in design, and those by mechanisms not considered in design. An example of the former is the failure of a piping component due to thermal transient stresses, while an example of the latter is the failure of a pipe due to damage accidentally inflicted during construction.

For pipe rupture protection, regulations dictate that only the former need be considered. Breaks are postulated at discrete, high-stress locations, and at known stress-raising points, such as junctions.

There is no guarantee, however, that breaks will be confined to these locations. A contrary principle argues that ruptures are more likely away from postulated high-stress locations, because fewer mitigating measures are taken in these areas. Without admitting the validity of this principle, it is reasonable to assume that there is a significant probability of ruptures occurring away from the presumed locations.

3.2 Orientation of Rupture

Two types of pipe rupture are postulated in current practice. The first is a circumferential break, in which the pipe is completely and cleanly severed through a plane normal to its axis. The second is a longitudinal break, in which the pipe remains contiguous, with an oval opening being formed in its wall. One produces a jet parallel to the pipe axis, the other, normal.

In reality, such precise ruptures will not occur. Cracks will form at random angles, will cause partial severance, and so on. The probability that the pipe or jet will behave in the postulated manner is, in all likelihood, very small.

3.3 Magnitude of Force

Two related fluid forces are of interest. The first is that imposed when the fluid jet strikes a target, and the second is the unbalanced fluid force on the ruptured pipe. The latter force causes the pipe to whip, and it is this phenomenon which is of principal concern here.

The magnitude of the force depends on the fluid state in the pipe, the pressure, the reservoir, and the break opening time. In pipe rupture analysis, a conservatively bounding estimation of this force is made. Principally, the conservatism is introduced by

the assumption that the full break opening area is formed in one millisecond. Fracture mechanics considerations indicate that this assumption is unreasonable, and that rupture will be considerably slower. The effect on the load magnitude is very large. This, coupled with the other conservatisms, leads to adoption of a design load that may be as much as an order of magnitude greater than the actual load.

3.4 Probability of Target Being Struck

In the example, two ruptures have been postulated. Assuming that both are circumferential ruptures, a probable restraint scheme is shown in Figure 2. Note that the ruptured pipe is assumed to whip in its own plane, and that the effect of pipe supports and impact with 'non-target' structures is disregarded.

Consider first the postulated rupture nearest the restraint. Assume that the rupture is truly circumferential and that the pipe does whip in its own plane. The restraint will consist of an energy absorber, the strength of which is dictated by the kinetic energy the pipe develops as it whips across the gap. This kinetic energy varies with the magnitude of the unbalanced fluid forces and with the width of the gap. Assuming that the restraint is a proprietary U-bar, design allowables dictate that only one quarter of its ultimate energy-absorption capacity be used. Thus, the probability that it will fail is extremely low. The support structure is designed to a conservative load combination, with an allowable stress of approximately 90 percent of yield. Given that the load is a short-duration, one-time event, and that plastic behavior of the material or the structure is not taken into account, the probability of its failure is similarly extremely small for the design load case.

Now consider the effect of varying the rupture location or orientation. Both will significantly increase the probability of the targets' being struck. For instance, should a rupture occur at any location in zone A of Figure 3, target 1 will probably be struck by a whipping pipe or by a fluid jet. Similarly, any rupture in zone B which causes slight out-of-plane whip or jet trajectories will lead to an impact on target 2. The probability of these interactions, given the rupture location and orientation, will be largely independent of the magnitude of the forcing function or the strength of the restraint, as the latter is not functioning to prevent the interaction.

4. Effectiveness of Current Criteria

Under the existing regulatory position, a relatively narrow band of possible ruptures is being restrained. The massiveness of the restraint devices and structures render it impractical to significantly widen this band. This massiveness arises because:

a. an extremely conservative load is being used for design, and
b. given this load, significant additional conservatism is being built into the device and structure.

It will be shown in the next section that removing those conservatisms has little effect on the overall risk. And, further, by reducing the massiveness of the restraints, it is possible to significantly reduce the overall risk by providing more restraints at no increase in cost.

5. Hypothetical Example

To illustrate the discussion, the effectiveness of a restraint system for a typical piping layout is considered more closely. The system is rudimentary and many of the

parameters are judgemental; however, the results do show the potential weakness of the current approach.

The piping layout, together with the two restraint schemes considered, is shown in Figure 4. Only longitudinal breaks are considered in this example, but the conclusions are applicable to circumferential breaks as well. Restraint scheme 'A' is typical of that which would be developed today. A longitudinal break has been postulated at an elbow, and a pair of energy-absorbing restraints placed there to prevent out-of-plane whip. These restraints have been assumed to be effective for breaks occurring around two-thirds of the pipe circumference; this is undoubtedly an optimistic estimate for many plants. Restraint scheme 'B' is, the authors consider, a more realistic approach. Ring-restraints, effective around the full pipe circumference, have been placed at regular intervals. With the conservative design loads currently in use, however, such ring-restraints are impracticable.

To consider the relative efficiency of these schemes, numerical estimates of three parameters were made. First, the probable break location was estimated. Second, the probable force imposed on the restraint was assessed. Third, the probability that the restraint would fail was calculated for a range of forces. To simplify the problem, a possible fourth parameter, the probability that a target would be struck, given that a restraint failed, was set to one.

5.1 Break Location

The pipe consists of two straight sections and a small-radius bend. Two break location probability functions were considered. In each case, the probability that the break would occur at any given location on the straight pipe, given that a break occurred, was uniform. Similarly, the probability was uniform around the bend. However, in one case, breaks were considered five times more probable on the bend (as opposed to the straight pipe); in the other case, twice as likely. These ratios were derived qualitatively from known stress levels, tempered by consideration of flaws and accidental damage. In both cases, the break was assumed to be equally probable at any point around the circumference.

5.2 Restraint Force

The probable force distribution assumed is shown in Figure 5. The mean force is set equal to 40 percent of the maximum force currently used for restraint design. The authors consider Figure 5 to be a conservatively severe estimate of the probable force magnitude, given the results of current fracture mechanics studies of the pipe rupture phenomenon.

5.3 Restraint Strength

The assumed relationship between the probability that a restraint will function (under a given force) and its design load is shown in Figure 6. This relationship reflects, at least partially, the effects of strain-hardening, design margin, and the plastic strength of redundant structures. Also, the effectiveness of a restraint was assumed to decrease linearly with its distance from the break. Restraints more than ten pipe diameters from the break were assumed to be ineffective.

5.4 Results

Eight cases were considered, four for each restraint scheme. For scheme 'A', two restraint design strengths were assumed, one corresponding to the maximum force as used in current practice, and one equal to half this value. For scheme 'B', restraint design

strengths equal to one-half and one-fifth this maximum force were considered. Each of these four cases was then evaluated for the two break location assumptions -- breaks two and five times more probable at the bend.

The results are summarized in Table 1. Values given represent the probability that the restraints will prevent an unacceptable interaction from occurring -- the higher this probability, the better the restraint scheme.

5.5 Discussion of Results

Four distinct observations can be made from the results in Table 1:

a. The susceptability of the bend to rupture (as opposed to the straight pipe) has little effect on the effectiveness of the restraints for the cases considered.

b. For restraint scheme 'A', the effect of halving the design strength is small.

c. For a similar level of design strength, restraint scheme 'B' is 3 to 4 times more effective than scheme 'A'.

d. Restraint scheme 'B', with design loads only 20 percent that of scheme 'A', is approximately twice as effective.

6. Conclusions

The provision of pipe rupture protection in nuclear power plants is closely regulated. In this paper, it is argued that these regulations do not serve to obtain the most effective protection for the capital cost invested in rupture protection. This argument has been supported by a simple but probably representative example.

Specifically, the authors contend that rupture restraint design loads required by existing regulations are much too high. Further, by reducing these loads, more rational and more effective restraint schemes become practicable without increase in cost.

	Restraint Scheme A		Restraint Scheme B	
Ratio of Restraint Strength to Maximum Force	1.0	0.5	0.5	0.2
Breaks 5x more probable on bend	0.23	0.22	0.68	0.40
Breaks 2x more probable on bend	0.18	0.17	0.66	0.38

TABLE 1 Probability that Restraints will Prevent Unacceptable Interaction

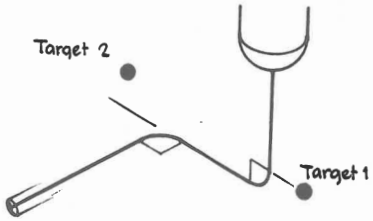

Figure 1 Simple Piping Layout

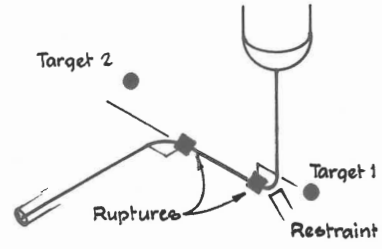

Figure 2 Typical Restraint Scheme

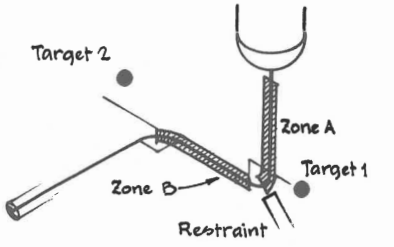

Figure 3 Damaging Rupture Locations

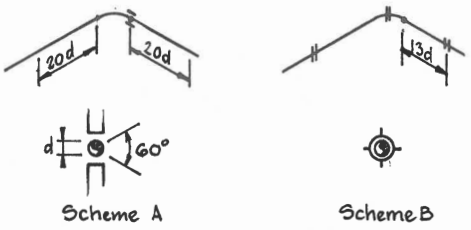

Figure 4 Piping and Restraint Layouts

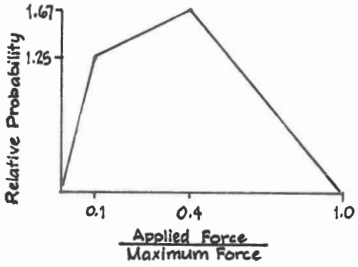

Figure 5 Applied Force Probability Distribution

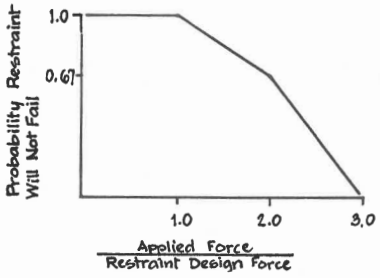

Figure 6 Restraint Strength Probability Distribution