Development And Application of a Risk Based Algorithm For Protection Against HELB Dynamic Effects

J. Van Vyve, C. Leblois
TRACTEBEL Engineering, Brussels, Belgium
G. Rousssel, P. Mignot
VINCOTTE ASBL, Brussels, Belgium

INTRODUCTION

A risk based algorithm to optimize the selection of the breaks to be postulated in the process of protecting a plant against the dynamic effects resulting from high energy line failure is presented. The method was applied for a safety reevaluation of three existing plants. A synthesis of the application to the Tihange 1 and Doel 1/2 units is given.

DEVELOPMENT OF THE RISK BASED ALGORITHM

General Design Criterion 4 of Appendix A to 10 CFR 50 requires that structures, systems and components important to safety be protected against dynamic effects that may result from equipment failures. The instruments to ensure protection against dynamic effects resulting from a High Energy Line Break (HELB) are : Regulatory Guide 1.46, SRP 3.6.1, SRP 3.6.2 and ANSI/ANS - 58.2.

In order to determine which locations in a high energy piping system shall be selected for postulated ruptures, these documents rely on criteria based on the stress level or the cumulative usage factor and, to calculate these, use the rules of the ASME B and PV Code, Section III.

They are however some basic reasons to consider this approach as inappropriate, two of them being summarized hereafter.

First, it is not felt that the usual stress based selection method is very satisfactory, as the review of actual pipe ruptures shows that most ruptures do not occur at locations of highest calculated stresses, but rather at locations of highest actual stresses in normal operation, which, most of the time are due to unexpected behaviour of the piping system resulting from human error, design error, unaccounted thermal loading, snubber freezing, etc.

Secondly, when requalifying an operating plant, physical separation is no more possible and a stress based approach could lead to numerous pipe whip restraints on small lines.

Basic Principles

The proposed method recognizes first that piping failure is likely to occur in overstressed areas but also that the stress report fails to predit the actual stresses in the piping wall. However geometrical discontinuities are known to induce stress concentrations and potential pipe rupture is therefore postulated at each discontinuity of a high energy line.

Then, the method aims at selecting which potential break locations are not to be further considered. To this end, the risk associated to each discontinuity is calculated according to the formula given in eq (1) hereafter. Clearly the different dynamic effects of a break (or interaction modes) are considered : jet impegement, pipe whip and environmental effects.

The method consists in ranking all potential interactions according to the risk and to take corrective actions or protection measures when (and only when) the risk exceeds a predefined value. The residual risk corresponding to all unprotected interactions is considered acceptable.

Risk based algorithm

Basically the risk associated to a given discontinuity j of some piping system i for a specified interaction mode l can be written

$$r_{ijl} = PR_{ij} \sum_{t} PD_{ijtl} * SC_{it} \qquad (1)$$

where the sommation is extended to all the critical targets with respect to the considered rupture and

PR_{ij} = probability of rupture of pipe i at point j
PD_{ijtl} = (conditional) probability of loss of function of target t due to the interaction mode l for a rupture of pipe i at point j
SC_{it} = safety concern, depending on the target and the initiating event, i.e. the ruptured piping i.

Probability of rupture PR_{ij}

It is assumed that the probability of rupture is equal to the probability to deviate from safe operating range multiplied by a factor depending on the local geometry of the discontinuity and material type

$$PR_{ij} = M_i G_j \gamma (P_m + P_h/Q_i) \qquad (2)$$

Deviation from safe operating range is assumed to be due to either the scatter of material properties or the human errors. The corresponding probabilities are named P_m and P_h.

The probability to deviate from safe operating range is obtained by summing them, taking into account that P_m can be reduced by performing controls or monitoring operation to increase the reliability. The relevant coefficient Q is defined with respect to the condition in non nuclear piping systems (Q = 1). Experience shows that P_m is very much lower than P_h. G_j is related to the stress-dependence of PR_{ij} and is assumed to be specific to each type of dicontinuity. G_j is actually defined as the ratio of fatigue damage between a given discontinuity and a straigth portion of a pipe run for identical loading conditions (see Table 1).

M_i takes into account the higher toughness of stainless steel with respect to carbon steel, giving a greater probability of leak before break (see Table 1).

The normalization factor γ is required because the values of the factors M_i and G_j are relative values. Compilations by various authors show that the annual rate of piping rupture in conventional power plants P_0 may be estimated to $1{,}5\ 10^{-3}$. Assuming that, in absence of any enhanced controls or monitoring requirements (Q = 1), the probability per year of a pipe rupture occurring in a nuclear power plant is equal to P_0, γP_h is found to be equal to

$$\gamma P_h = P_0 / \sum_{ij} M_i G_j$$

Safety concern factor SC_{it}

The safety concern factor SC_{it} quantifies the importance of the target t to the safety of the plant in the case where pipe i has failed. It is assumed that SC_{it} may be expressed as the product of two factors :

$$SC_{it} = S_{it} \cdot E_{it} \qquad (3)$$

The evolution factor E_{it} is taken equal to 1.0 when damaging the target t leads directly to the violation of a basic design criterion. A value of 0.1 is taken when a concurrent failure of an active component is required in order to transgress a basic design criterion.

The safety weight factor S_{it} considers that the weight of the various basic design criteria may be different depending on the initiating event and the impact on the safety. More specifically it is based on the ultimate concern of offsite radioactive release. The safety weights are proposed to be ranked among three categories and to attribute to these the values : 1, 0.3 and 0.1.

Assessment of PD_{ijtl}

The summation appearing in eq (1) is rearranged by first putting together all the terms with equal value of the safety concern factor SE and then by factorizing $(SE)_k$ in each group. The coefficient of each specific $(SE)_k$ is found to be the expected number of critical targets with safety concern factor $(SE)_k$ damaged through a specified interaction mode l when pipe i has failed at point j and is called N_{ijkl} . So,

$$\sum_t PD_{ijtl} \cdot SC_{it} = \sum_k N_{ijkl} \cdot (SE)_k \qquad (4)$$

The number N_{ijkl} is assessed on a probabilistic basis and it is referred therein to the average number of interactions counted in the detailed HELB analyses of recent PWR's. A model is constructed where the critical targets are uniformly distributed in the space and all critical targets within a "volume affected by a break" loss their function when the pipe i is ruptured at discontinuity j.

The number N_{ijkl} is therefore assessed on basis of

- a determined expression for the "volume by a affected break" V specific to each pipe for each interaction mode

$$V = \beta_l \left(\frac{P_i A_i^{1.5}}{10}\right) \qquad (5)$$

  where P_i and A_i are respectively the pressure and pipe inside area and the product is expressed in kN. β_l depends on the interaction mode (see Table 1).
- an evaluation of the density of critical targets D obtained from the detailed analyses performed for recent 3 loops PWR's. A density of $1,4.10^{-3}$ critical targets per cubic meter was adopted.
- an assumption of the distribution of the critical targets with respect to the safety concern factor.

Threshold K_0

In order to determine the threshold above which protection against potential pipe rupture is required, a reference plant is defined, in terms of

- Typical distribution of high energy piping (diameter, schedule, length, pressure, material, Q coefficient)
- Typical ratios of discontinuities per meter of pipe.

The global risk R for the reference plant is then calculated by summing eq (1) for all pipes, discontinuities and interaction modes.

$$R = \sum_{ijl} r_{ijl} \qquad (6)$$

Defining the normalized individual risk K_{ijkl} as the risk corresponding to a break of pipe i at location j for an interaction mode l and a given value $(SE)_k$ of the safety factor and divided by γP_h i.e.

$K_{ijkl} = \alpha_{ij} D\beta_l (SE)_k$, with the risk index $\alpha_{ij} = \frac{M_i G_j}{Q_i} \left(\frac{P_i A_i^{1.5}}{A_s}\right)$

and rearranging the summation of eq (5) in increasing order of individual risk, the global risk is rewritten as

$$R = \gamma P_h \sum_{K_{min}}^{K_{max}} n(K) \cdot K \qquad (7)$$

where n(K) is the number of breaks corresponding to the individual risk K. If it is decided that protection measures will be taken only for potential pipe break locations with an individual risk K greater than K_0 the total accepted risk will be

$$R_0 = \gamma P_h \sum_{K_{min}}^{K_0} n(K) \,.\, K \qquad (8)$$

REFERENCE CURVE (K_0, R) AND SENSITIVITY STUDY

The (K_0, R) curves for the reference plant were established using conservative assumptions for distribution of targets between S and E values. These curves are drawn on figures 1 (global risk) and 2 (risk in whip). Curves with a vertical shift of $\sqrt{10}$ (half order of magnitude) are drawn on both sides. A sensitivity study, aimed at identifying the effect on the (K_0, R) curve for variation of all the parameters and distributions was also performed. Even for variation of up to 100 %, the effect on the (K_0, R) curves remained low, as it lead most of the time to the shift of individual risks to higher or lower values, which corresponds to a diagonal shift of the curve in a (K_0, R) diagram, so that the corresponding curves always fell well between the limit curves of figures 1 and 2.

Finally, the (K_0, R) curves were drawn on figures 1 and 2, for a plant having the characteristics of the Tihange 1 sample (see hereafter). Even with the highly disturbed distribution of that sample, the curves fall well between the limits.

PRACTICAL APPLICATION TO THE SAFETY REEVALUATION OF DOEL 1, DOEL 2 AND TIHANGE 1

Plant Description and Technical Data

Doel 1/2 (2 loops, 2 x 390 MWe PWR) and Tihange 1 (3 loops, 870 MWe PWR) started operation in 1974/1975 and were therefor designed before issuance of R.G. 1.46 and following rules for protection against dynamic effects of breaks in high energy lines. Pipe whip restraints were only installed on part of high energy lines (primary loops, main steam, feedwater).

In 1984, the safety authorities requested to extend the high energy line break (HELB) analysis to all the high energy lines, according to the existing rules. This was achieved by using the new risk based method.

Working procedure

A value of K_0 = 1 was adopted for the practical application of the method. This value corresponds (fig. 1) to an accepted risk R_0 of 10^{-5} violation of a major (SE = 1) basic design criterion per year. The corresponding threshold values of the risk index α are 4.3 (environment), 64 (pipe whip) and 710 (jet).

Value of weight factor (S) was defined for each safety criterion, high energy lines were listed from P & ID's and discontinuities with α higher than 64 were identified on the isometrics (environmental effects were considered separately).

The critical targets around each discontinuity were then identified from layout drawings and walkdowns during plant outage, and the actual risk for each target was calculated from its S and E coefficients. Evaluation grids where then used to define for each target the level of protection required and corrective actions or protection measures were taken (rerouting, system change, pipe whip restraints, jet shield ...), like in a conventional HELB analysis.

Due to the risk based approach of the method, the evaluation work concentrates on the points with a high level of associated risk, so that most of dicontinuities in small size pipes are discarded on the base of the value of the risk index α.

Comparison of Results to the Reference Plant

The (K_0, R) curves of Figures 1 and 2 were established using the physical characteristics of a "reference plant".

When applying the method to an existing plant, the problem is to know if the actual values for the existing plant are within the assumptions of the reference plant and the sensitivity study.

But these actual data are obviously not known and it would require an unreasonable amount of work to collect them, while this could be done for a sample of piping, taking into account the bias introduced in the results.

For purpose of validation, this was performed for the SI/RHR system of Tihange 1 in the reactor building, representing 165.7 m of high energy piping in the range 2" to 12". It was possible for this sample to establish the distribution of discontinuities per meter of pipe (distribution of factor G), as well as of the safety factor (S) and evolution factor (E) for the identified critical targets.

Table 2 gives the total number of pipe breaks and interactions in whip for the given sample, where the protection threshold value of 1 was exceeded, with a comparison to the probable figures based on the standard distribution of G, E and S factors for the reference plant, and shows that application of the method led to about twice the number of predicted critical breaks and interactions.

This essentially results from the bias effect due to the location of the sample in a critical area of the plant (primary loop cells) where most of the targets have S and E values higher than the conservative figures of the reference plant.

To achieve the comparison, the probable figure of breaks and interactions and the cumulative risk curves were established using the actual distributions of G, S and E instead of the standard ones. Results are given in table 2 and on figures 1 and 2 (curves denoted "Tihange 1").

The number of pipe breaks was also established from the rules of S.R.P. 3.6.2

- on the base of the stress level rules (break locations estimated from equivalent systems in newer plants, assuming a minimum number of intermediate breaks),
- on the base of the rules for non nuclear piping (break at each valve, fitting, welded attachment, terminal end).

Results are given in table 2 and compared to the actual values. It can be seen that probable and actual figures remains in good agreement, while the stress based approach of S.R.P. (should the ASME stress reports have been available) gives a lower number of breaks, most of them being located at points identified by the risk based method. Fitting based approach however gives a larger number of breaks, even on this large bore sample, and clearly shows the benefit of using the risk based method for small bore piping.

Reasons and Extend of the Corrective Actions

The principles governing the risk based methodology lead to point out in the application the interactions where either the safety concern (S.E product), the probability of rupture or the damaging capability is high.

The results are that the application to the Doel 1, Doel 2 and Tihange 1 plants quickly identified the major HELB problems, that were finally concentrated in very localised areas of the plants.

These areas are as follows (with major targets between brackets) :

For Doel 1 and Doel 2 :

- breaks in the pressurizer surge line (SG supports and SI lines)
- breaks in the main steam and feedwater lines in the containment isolation valves area (containment isolation)
- breaks at blow down piping terminal ends (cable trays).

For Tihange 1 :

- breaks in the SI/RHR system in the primary containment (SI/RHR common mode failures due to interactions; cable trays)
- auxiliary feedwater (common mode failure; cable trays)

This mostly affects large size lines. It has to be pointed out that cable trays were often identified as critical targets. This was related to the lack of physical separation at plant design stage.

The total number of protective structures that were installed in the plants are 88 restraints and 5 jet shields for Doel 1 and 2 (total) and 28 restraints and 6 jet shields (plus modification of the high head safety injection system to hot and cold legs, representing suppression of about 20 restraints) for Tihange 1.

TABLE 1 - Standard coefficients

M	: .3	stainless steel	
	1	carbon steel	
G	: .3	reinforced pipe section	
	: 1	straight run or flush weld	
	: 3	bend (R/d ≥ 3), weld	
	: 10	elbow (R/d < 3)	
	: 30	thickness transition, valve, attachment	
	: 100	tee, branch, axisymmetric attachment	
	: 300	terminal end	
Q	: 1	non ASME piping, ASME with a minimum basic QA	
	: 3	ISI + vibration and displacement control	
	: 10	specific and reinforced ISI on this discontinuity	
	: 30	local leak detector	
V	: Vo	jet	$Vo = (PA/10)^{1.5}$
	: 11 Vo	whip	(PA in KN)
	: 165 Vo	environment	

TABLE 2 - Number of pipe breaks and critical interactions

Item	Actual (Tihange 1) results	Probable figures from standard distribution of G, S, E	Probable figures from actual distrubtion of G, S, E	SRP stress rules	SRP NN piping rules
Breaks	71	31	80	40	108
Interactions	213	137	325	-	-

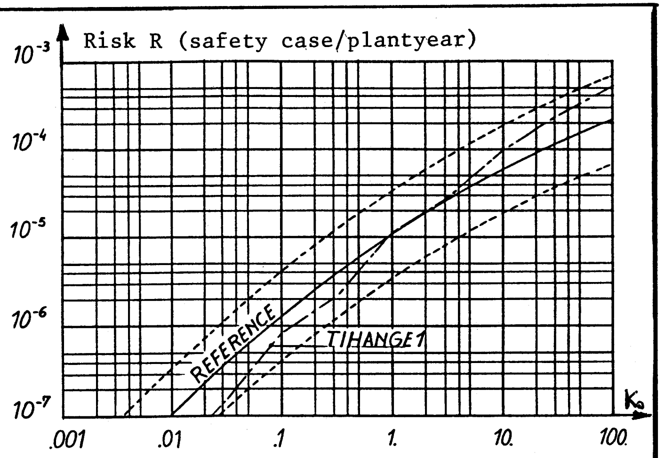

Figure 1 - Cumulative Risk R versus protection threshold

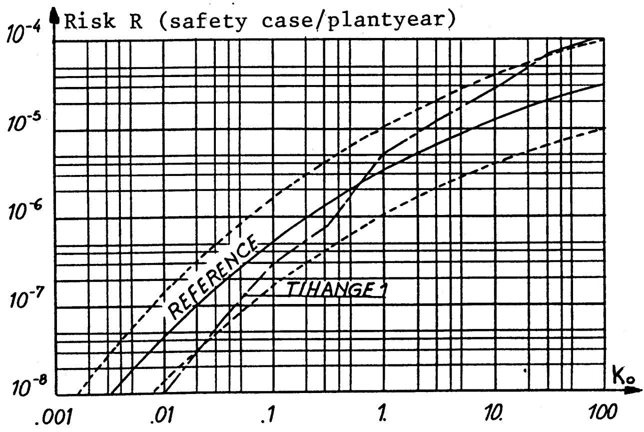

Figure 2 - Cumulative Risk R in whip versus protection threshold