STUDY ON RISK-INFORMED IN-SERVICE INSPECTION FOR PWR

Tamio Koriyama[1], Haruo Fujimoto[1]

[1]*Regulatory Standard and Research Department, Secretariat of Nuclear Regulation Authority: Roppongi-First Bldge., 1-9-9 Roppongi, Minato-ku, Tokyo, Japan, 106-8450 tamio_koriyama@nsr.go.jp, haruo_fujimoto@nsr.go.jp*

As the value of insights obtained from PRA is recognized, risk information has been widely utilized in nuclear regulation around the world. In this paper, risk-informed in-service inspection (RI-ISI) for piping is discussed focusing on two RI-ISI methodologies (the WOG methodology developed by Westinghouse Owners Group (WOG) and the EPRI methodology developed by Electric Power Research Institute (EPRI)).

A new methodology was developed by the modification of the following 3 models in the WOG methodology for; (1) piping rupture probability, (2) categorization criteria for Risk Reduction Worth (RRW) of each piping segment using surrogate events to determine its risk significance, and (3) degradation mechanisms to determine its rupture importance. Replacing probabilistic fracture mechanics analyses adopted for (1) in the WOG methodology, the piping failure data collected in the OECD/NEA Piping Failure Data Exchange (OPDE) project and the hierarchical Bayesian method were used to obtain piping rupture probabilities more appropriately reflecting plant operational experiences. For (2) in the WOG methodology, RRWs categorize risk significance of piping segments as follows; RRW > 1.005: high risk significance, 1.001 ≤ RRW ≤ 1.005: the risk significance is left to the judgment of experts, RRW < 1.001: low risk significance. Because the dependence on the judgment of experts might make random categorization, 1.001 ≤ RRW ≤ 1.005 is divided to high or low risk significance in accordance with high or low rupture importance described later, respectively. Although (3) in the WOG methodology adopts 10 types of degradation mechanism, 16 types of degradation mechanism were specified more appropriately reflecting plant operational experiences from the piping failure data collected in the OPDE project, i.e. flow accelerated corrosion, intergranular stress corrosion cracking, high cycle fatigue, etc. Among them, the mechanisms which are active and highly susceptible to rupture were considered to have high rupture importance, while the others were considered to have low rupture importance. Piping segment selection matrix composed of RRWs and rupture importance demarcates high-safety-significant piping segments from the low-safety-significant ones.

For the inspection of piping in ISI, surface or volumetric examinations are required for weld joints in these high-safety-significant piping segments in addition to the leak examinations and the visual testing for the whole piping segments. While safety significance of each piping segment is determined qualitatively based on experience in the traditional deterministic ISI methodology, RI-ISI methodologies are characterized by the determination of quantitative risk-informed safety significance of each piping segment. The modified WOG methodology and EPRI methodology were applied to a 4-loop PWR plant. The modified WOG methodology gave the similar portions and numbers of piping segments subject to the surface or volumetric examinations to the EPRI methodology. The RI-ISI methodologies have the possibility to enable to identify hidden high-safety-significant piping segments in the traditional ISI such as hidden high-safety-significant piping segments in component cooling water system. The rupture probability in the modified WOG methodology can directly reflect plant operational experiences by utilization of existing piping failure data.

I. INTRODUCTION

As the value of insights obtained from PRA is recognized, risk information has been widely utilized in nuclear safety regulation around the world. In the area of inspection of NPPs, it is investigated how to use risk insights in order to realize efficient and effective inspection. Risk-informed in-service inspection (RI-ISI) for piping is a success outcome in this area. In this paper, RI-ISI is discussed focusing on two RI-ISI methodologies in comparison with the traditional in-service inspection (ISI) methodology[1]. One is WOG methodology[2] developed by Westinghouse Owners Group (WOG) and the other is EPRI methodology,[3, 4] developed by Electric Power Research Institute (EPRI). In this paper some modifications were made to the original WOG methodology and it is called the modified WOG methodology.

The following Chapter II discusses safety significance of piping segments used in ISI methodologies. Chapter III describes the modification of WOG methodology. Chapter IV shows the elements of the EPRI methodology. Chapter V discusses the comparison of the results which are derived from the application of the modified WOG methodology, the EPRI methodology, and the traditional ISI methodology to a 4-loop PWR plant. In Chapter VI, the present study is concluded.

II. SAFETY SIGNIFICANCE OF PIPING SEGMENTS USED IN ISI METHODOLOGIES

One of the necessary steps in ISI methodologies is the categorization of safety significance of piping segments. As a result of this step, piping segments are separated into high-safety-significant ones and low-safety-significant ones. In the traditional ISI methodology, Class 1 and 2 pipes are categorized, in principle, as high-safety-significant piping segments deterministically, whereas other pipes are categorized as low-safety-significant piping segments. On the other hand, in the RI-ISI methodologies, rupture probabilities of piping segments and effects of piping segment ruptures are evaluated to determine safety significance of piping segments. A surface test or a volumetric test of weld joints is enforced to do for the high-safety-significant piping segments in addition to a leak test and a visual testing (VT) which are required to all of pressure retaining piping segments.

III. DEVELOPMENT OF THE MODIFIED WOG METHODOLOGY

The modified WOG methodology was developed by the modification of two elements used in the WOG methodology. One is the method to evaluate rupture probability of piping segment and the other is the categorization of safety-significant piping segment. As described in Chapter II, the inspection subjects and test methods are determined so that a surface test or a volumetric test is required for weld joints in the high-safety-significant piping segments in addition to a leak test and a VT which are required to all of pressure retaining piping segments.

III.A. Rupture Probability of Piping Segment

Instead of probabilistic fracture mechanics (PFM) evaluation adopted in the original WOG methodology, the piping failure data collected in the OECD/NEA Piping Failure Data Exchange (OPDE) project[5] in conjunction with hierarchical Bayesian method[6] were used to obtain piping segment rupture probabilities in the modified WOG methodology in order to reflect plant operational experiences. In the meantime, the PFM evaluation has the possibility to estimate the effect of inspection on the piping segment rupture probabilities.

As for OPDE data, 1,778 piping failure incidents occurring at PWRs included in the OPDE database version as of 31-December-2009 were used as the observed data for Bayesian approach.

The hierarchical Bayesian method was applied to derive piping segment rupture probabilities. It embodies a complete Bayesian approach to the problem of estimating the unknown population-variability distribution based on the observed data. The piping segment rupture probability $p = (p_1, \cdots p_i \cdots, p_N)$ for the plant i can vary among N plants, although they resemble each other. This is modeled by a distribution g that describes the population variability and produces values p_1 through p_N. The parameters of the population-variability distribution are called hyperparameters, which can be expressed by $q = (q_1, \cdots, q_m)$. The hierarchical Bayesian method expresses the initial uncertainty about the unknown hyperparameters using a hyperprior distribution. $p = (p_1, \cdots p_i \cdots, p_N)$ and $q = (q_1, \cdots, q_m)$ are obtained by the hierarchical Bayesian method. For observed available data $E = (E_1, \cdots E_i \cdots, E_N)$ for the plant i, a joint posterior distribution $f(p, q \mid E)$ of p and q is described[7] by Eq. (1) based on Bayes' Theorem.

$$f(p,q \mid E) = \frac{L(E \mid p) f_{pri}(p \mid q) f_{pri}(q)}{\int_p \int_q L(E \mid p) f_{pri}(p \mid q) f_{pri}(q) dp dq} \tag{1}$$

$L(E \mid p)$: a likelihood function of piping segment rupture probability p given observed available data E

$f_{pri}(p \mid q)$: a prior distribution of piping segment rupture probability p under the condition of hyperparameters q
$f_{pri}(q)$: a prior distribution of hyperparameters q that is the hyperprior distribution

The denominator in Eq. (1) is a normalizing constant. The characteristics of the piping failure data can lead the assumptions that p_i is independent of $\{E_j, p_j\}_{j\neq i}$ given hyperparameters q and E_i is independent of $\{q, E_j, p_j\}_{j\neq i}$ given p_i. Therefore, Eq. (1) can be written as Eq. (2).

$$f(p,q \mid E) = C\prod_{i=1}^{N} L(E_i \mid p_i) f_{pri}(p_i \mid q) f_{pri}(q) \tag{2}$$

$$C = \frac{1}{\int_p \int_q L(E \mid p) f_{pri}(p \mid q) f_{pri}(q) dp dq}$$

$L(E_i \mid p_i)$: a likelihood function of piping segment rupture probability p_i given observed available data E_i of each plant i
$f_{pri}(p_i \mid q)$: a prior distribution of piping segment rupture probability p_i of each plant i under the condition of hyperparameters q

The piping segment rupture probability p_i of each plant i can be obtained by integrating Eq. (2) for $p_j (j \neq i)$ and hyperparameters q as Eq. (3).

$$\begin{aligned} f(p_i \mid E) &= CL(E_i \mid p_i)\int_{p_1} \cdots \int_{p_{i-1}} \int_{p_{i+1}} \cdots \int_N \int_q dp_1 \cdots dp_{i-1} dp_{i+1} \cdots dp_N dq \\ &\quad \times f_{pri}(p_i \mid q) \prod_{j\neq i} L(E_j \mid p_j) f_{pri}(p_j \mid q) f_{pri}(q) \\ &= CL(E_i \mid p_i)\int_q f_{pri}(p_i \mid q) L(E_1,...,E_{i-1},E_{i+1},...,E_N \mid q) f_{pri}(q) dq \end{aligned} \tag{3}$$

$$L(E_1,...,E_{i-1},E_{i+1},...,E_N \mid q) = \prod_{j\neq i} \int_{p_j} L(E_j \mid p_j) f_{pri}(p_j \mid q) dp_j \tag{4}$$

For the population-variability distribution g of p_i, the log-normal distribution is used, because p_i has some limit for low values but no definite limit for high values, as Eq. (5).

$$f_{pri}(p_i \mid q) \equiv f_{pri}(p_i \mid \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} \frac{1}{p_i} \exp\left\{ -\frac{(\ln p_i - \mu)^2}{2\sigma^2} \right\} \tag{5}$$

In Eq. (5), μ and σ represent mean and standard deviation of $\ln p_i$, respectively. For the hyperprior distributions of μ and σ, uniform distributions of Eq. (6) and Eq. (7) are adopted in a position of no information and the hyperparameters q are $(a_\mu, b_\mu), (a_\sigma, b_\sigma)$.

$$f(\mu) = \frac{1}{b_\mu - a_\mu} \qquad a_\mu \le \mu \le b_\mu \tag{6}$$

$$f(\sigma) = \frac{1}{b_\sigma - a_\sigma} \qquad a_\sigma \le \sigma \le b_\sigma \tag{7}$$

Observed available data in each plant i are composed of the piping segment rupture incident number x_i and the exposure time, i.e. operating reactor year T_i obtained from the piping failure data. Under these conditions, the likelihood function of piping segment rupture probability p_i can be expressed by the Poisson process as Eq. (8).

$$L(E_i \mid p_i) \equiv f(x_i; p_i, T_i) = \exp(-p_i T_i) \frac{(p_i T_i)^{x_i}}{x_i!} \tag{8}$$

Equations from (4) to (8) were applied to Eq. (3) and integration was made by Markov Chain Monte Carlo (MCMC) simulation. For this computation, the publicly available software WinBUGS[8] (The Windows version of Bayesian inference Using Gibbs Sampling) code was used.

III.B. Effect of Piping Segment Rupture

For the evaluation of the effects of piping segments rupture, the original WOG method was used in the modified WOG methodology. In this method, a conditional core damage probability (CCDP) or a change in core damage frequency (△CDF) evaluated for the failure of a surrogate component obtained from existing PRA results is used for a CCDP or a △CDF from a piping segment rupture. The core damage frequency (CDF) due to the piping segment rupture is obtained as the product of CCDP and a piping segment rupture frequency or △CDF and a piping segment rupture probability.

III.C. Category of Safety-Significant Piping Segment

Risk reduction worth (RRW) derived from CDF is used as a metric to categorize safety-significance of piping segment in the original WOG methodology and this metric remains in the modified WOG methodology. On the other hand, the categorization criteria for RRW are changed in the modified WOG methodology from the original WOG methodology. As the categorization criteria of RRW of the original WOG methodology are; RRW > 1.005: high risk significance, 1.001 ≤ RRW ≤ 1.005: the risk significance is decided by the expert judgment, RRW < 1.001: low risk significance. In the modified WOG methodology, however, the region of 1.001 ≤ RRW ≤ 1.005 is divided into two regions, i.e. high and low risk significance area, using rupture importance described later, to avoid ambiguous discrimination caused by the expert judgment.

Another modification made in the modified WOG methodology is the categorization of degradation mechanisms to determine the importance of rupture. In the original WOG methodology 10 types of degradation mechanisms are adopted, while 16 types of degradation mechanisms are specified in the modified WOG methodology to reflect plant operational experiences from the piping failure data collected in the OPDE project more precisely. these 16 types of degradation mechanisms include a) erosion, b) corrosion, c) flow accelerated corrosion or erosion/corrosion (FAC), d) microbiologically induced corrosion (MIC), e) intergranular stress corrosion cracking (IGSCC), f) transgranular stress corrosion cracking (TGSCC), g) primary water stress corrosion cracking (PWSCC), h) boric acid induced stress corrosion cracking (B/A-SCC), i) thermal fatigue (TF), j) high cycle fatigue, k) other stress corrosion cracking (SCC), l) low cycle fatigue, m) fretting fatigue, n) severe overloading, o) human factor (HF), and p) unknown. Among them, the mechanisms from a) to j) which are active and highly susceptible to rupture are considered to have a high rupture importance, while the others are considered to have a low rupture importance.

Piping segment selection matrix composed of RRWs and rupture importance can demarcate high-safety-significant piping segments from the low-safety-significant ones. As shown in Fig. 1, six regions exit for placing the piping segments in the modified WOG methodology instead of four regions in the original WOG methodology. The piping segments in Region 1 and 2 are categorized as high-safety-significant and ones in Region 4B as low-safety-significant in the same way as the original WOG methodology. Although the piping segments in Region 3A and 4A are left to the judgment of experts in the original WOG methodology, ones in Region 3A are categorized as high-safety-significant and ones in Region 4A as low-safety-significant in the modified WOG methodology reflecting rupture importance. While the piping segments in Region 3B should be considered in accordance with an owner defined program in the original WOG methodology, they are categorized as low-safety-significant in the modified WOG methodology, reflecting low risk significance.

IV. ELEMENTS OF THE EPRI METHODOLOGY

The EPRI methodology was used in this study with no modification. As described in Chapter II, the inspection subjects and test methods are determined so that a surface test or a volumetric test is required for weld joints in the high-safety-significant piping segments in addition to a leak test and a VT which are required to all of pressure retaining piping segments. The EPRI methodology is briefly described below.

IV.A. Rupture Probability of Piping Segment

In the EPRI methodology, degradation mechanisms in a piping segment are identified in consideration of material, operating temperature and pressure, geometrical configuration, fabrication practices, fluid conditions, chemical environment, etc. They are categorized into TF, SCC, localized corrosion (LC), and flow sensitive (FS). TF includes thermal stratification, cycling and striping (TASCS) and thermal transients (TT). SCC includes IGSCC, TGSCC, external chloride induced stress corrosion cracking (ECSCC), and PWSCC. LC includes MIC, pitting (PIT), and crevice corrosion (CC). FS includes erosion-cavitation (E-C) and FAC.

The EPRI RI-ISI classification scheme for assignment of segments to three general classes of rupture potential is depicted as follows: if a piping segment is subject to FAC, the pipe rupture potential for the segment is classified as high, if a piping segment is subject to TF, SCC, LC, or E-C, the pipe rupture potential for the segment is classified as medium, and if there is no known degradation mechanism in a piping segment, the pipe rupture potential for the segment is classified as low.

IV.B. Effect of Piping Segment Rupture

In the EPRI methodology, a concept of consequence category is used to show the effect of piping segment rupture. This consequence category is defined by CCDPs associated with the impact of specific piping segment rupture. There are four consequence categories in this methodology; i.e. high consequence rupture for $CCDP > 10^{-4}$, medium consequence rupture for $10^{-6} < CCDP \leq 10^{-4}$, low consequence rupture for $CCDP \leq 10^{-6}$, and none for ruptures that have no effect on risk. CCDPs are obtained by the same way as the modified WOG methodology described in Section Ⅲ.B. The product of $\triangle$CDF and exposure time also gives CCDP. The exposure time is the sum of the allowed outage time (AOT) and the time to detect the rupture.

IV.C. Category of Safety-Significant Piping Segments

In the EPRI methodology, there are seven risk categories composed of three degradation mechanism categories and four consequence categories, which are shown in Table 1. In addition these 7 risk categories are assigned to three risk ranking; i.e. risk categories 1, 2, 3 are characterized as high risk, risk categories 4, 5 are characterized as medium risk, and risk categories 6, 7 are characterized, as low risk. Piping segments which are ranked as risk high and risk medium, i.e. risk categories 1 to 5, are considered to be high-safety-significant and those in risk low, i.e. risk categories 6 and 7, are considered to be low-safety-significant.

V. APPLICATION OF RI-ISI METHODOLOGIES TO A 4-LOOP PWR PLANT

The modified WOG methodology and the EPRI methodology were applied to a 4-loop PWR plant, in comparison with the application of the traditional ISI methodology. A study of internal event level 1 PRA during power operation[9] was used in this study. Systems to be evaluated are reactor coolant system (RCS), high pressure injection system (HPIS), low pressure injection system (LPIS), accumulator injection system (ACC), chemical volume control system (CVCS), pressurizer pressure control system (PPCS), compressed air system for control (CASC), containment spray system (CSS), auxiliary feed water system (AFWS), component cooling water system (CCWS), sea water system (SWS), main feed water system (MFWS), main steam system (MSS), containment recirculation system (CRS), and air conditioning chiller water system (ACCWS).

Trial PFM predictions of piping segment rupture probabilities showed relatively good agreement with piping segment rupture probabilities derived by Hierarchical Bayesian method by using of OPDE piping failure data for some small diameter pipes but there were differences of orders for medium or large diameter pipes. It is noted that the differences should be resolved by further studies.

Although a piping segment belonged to Class 3 in the traditional ISI methodology, volumetric examinations were assumed to be applied subject to Rules on Pipe Wall Thinning Management[10] in case that the segment was exposed to FAC.

The results of this study are shown Fig. 2 and Fig. 3. Fig. 2 shows the numbers of piping segments which are required to perform surface or volumetric test for weld joints. They are shown as the ratio to those of the traditional ISI. As shown in Fig. 2, the numbers of piping segments subject to the surface or volumetric tests are almost same between the modified WOG and EPRI methodology whereas these are about one thirds of those of the traditional ISI.

Fig. 3 shows the numbers of piping segments with surface or volumetric tests required for weld joints in the traditional ISI methodology, the modified WOG methodology, and the EPRI methodology as the ratio to the total segment numbers in each system. There are no piping segments in CCWS subject to surface or volumetric test required for weld joints in the traditional ISI because this system is classified as safety class 3. However, tests are required in the modified WOG and EPRI methodologies due to importance of this system. The OPDE database for PWRs gave some piping failure incidents in CCWS, so that this system has high risk in the modified WOG methodology. In the EPRI methodology, because degradation mechanisms such as TASCS and E-C were found in CCWS, the pipe rupture potential in this system is classified as medium. Although the numbers of piping segments with surface or volumetric tests required for weld joints were same both in the modified WOG methodology and the EPRI methodology in ACC, there were differences of degradation mechanism in the piping segments of ACC so that the modified WOG methodology showed erosion, corrosion, IGSCC, TGSCC, TF, high cycle fatigue, fretting fatigue, and HF and the EPRI methodology showed TASCS.

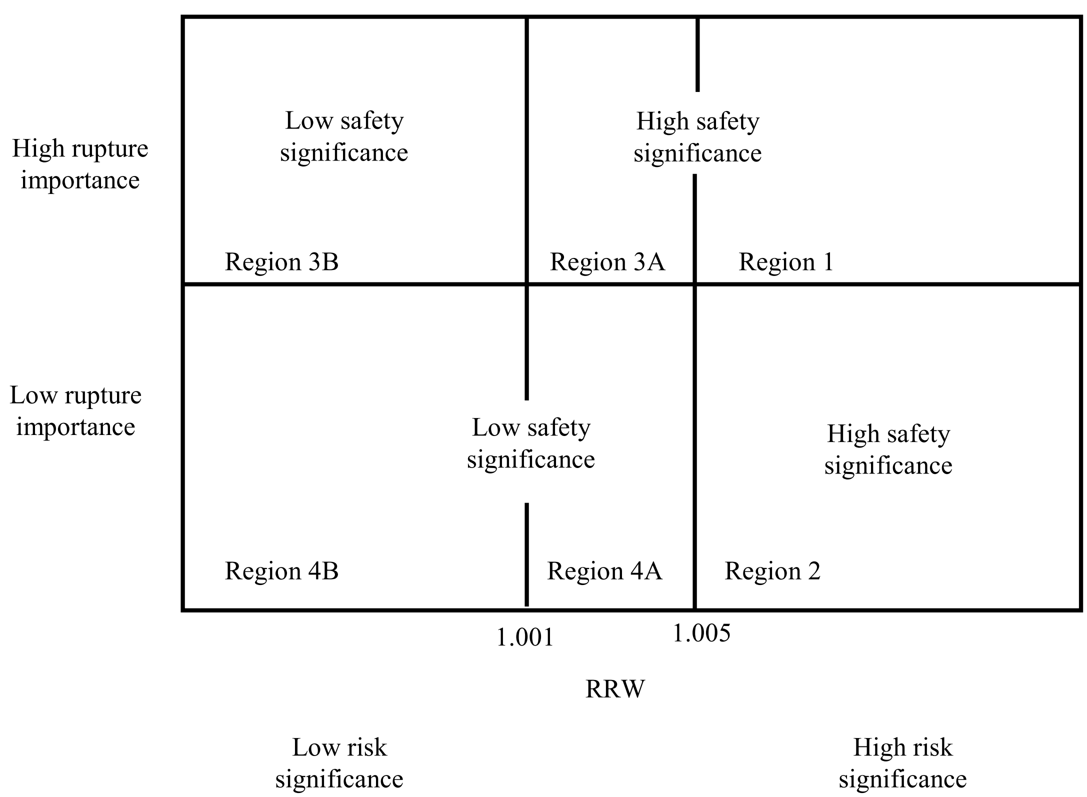

Fig. 1 Piping segment selection matrix in the modified WOG methodology

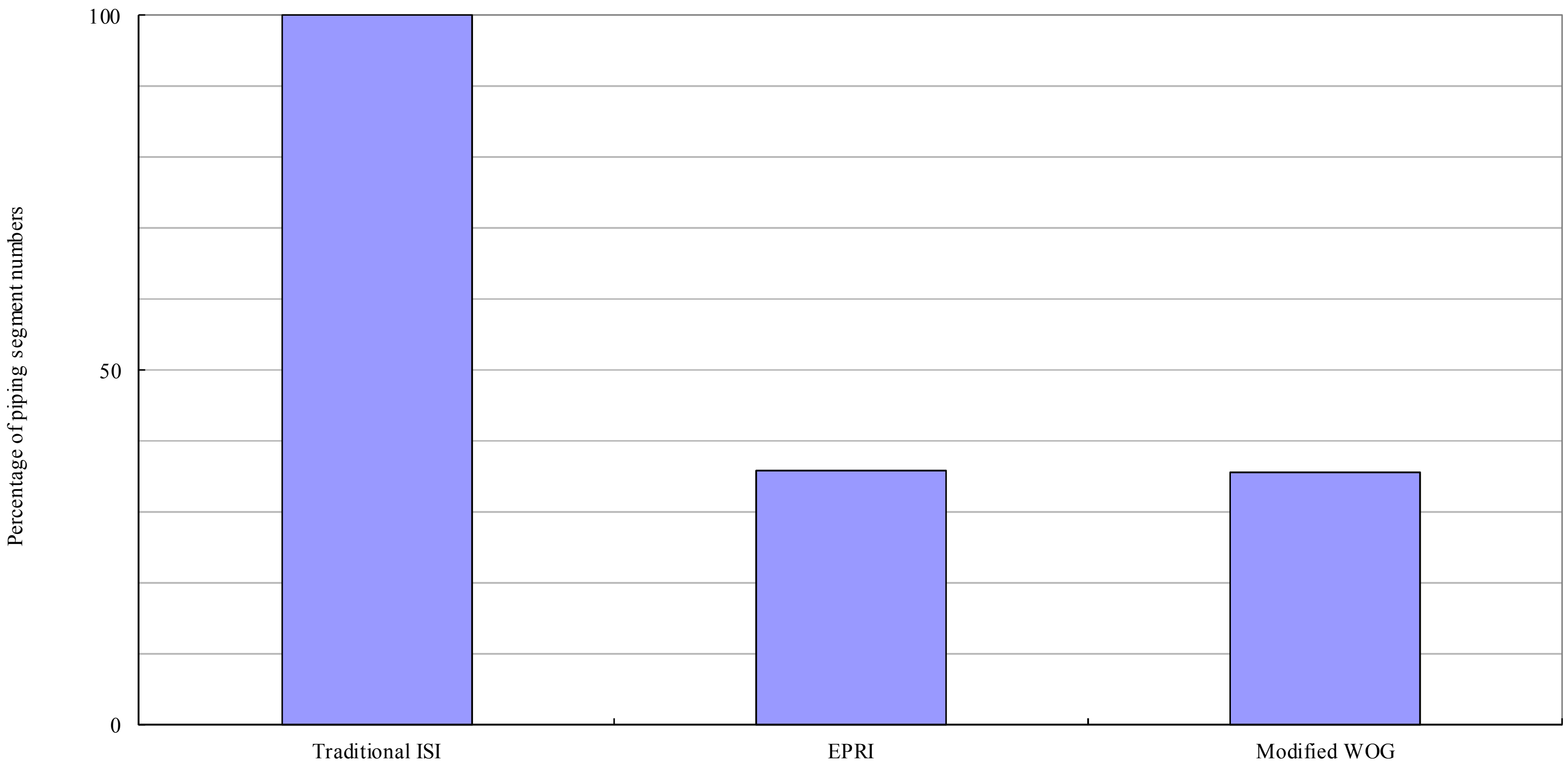

Fig. 2 Numbers of piping segments where surface or volumetric tests are required
(Normalized to numbers of piping segments in traditional ISI)

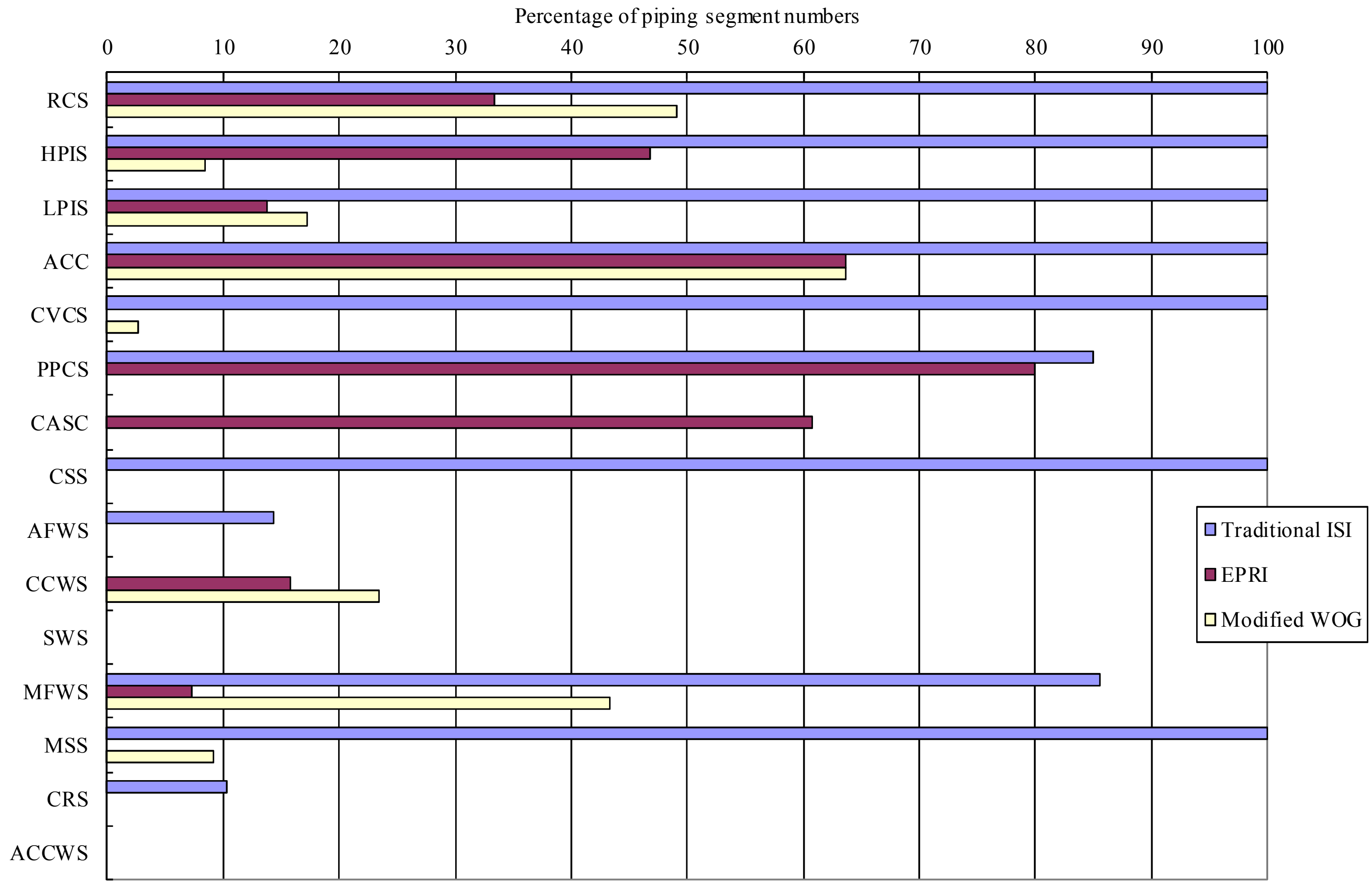

Fig. 3 Numbers of piping segments where surface or volumetric tests are required in each system
(Normalized to the total numbers of piping segments in each system)

Table 1 Matrix for segment risk characterization in the EPRI methodology

Potential for pipe rupture	Consequences of pipe rupture			
	None	Low	Medium	High
High	Low Category 7	Medium Category 5	High Category 3	High Category 1
Medium	Low Category 7	Low Category 6	Medium Category 5	High Category 2
Low	Low Category 7	Low Category 7	Low Category 6	Medium Category 4

VI. CONCLUSIONS

The two RI-ISI methodologies, which are the modified WOG methodology and the EPRI methodology, were applied to a 4-loop PWR plant. The modified WOG methodology gave the similar numbers and portions of piping segments subject to the surface or volumetric tests to the EPRI methodology. The RI-ISI methodologies have the possibility to enable to identify hidden high-safety-significant piping segments in the traditional ISI such as hidden high-safety-significant piping segments in CCWS. The rupture probability in the modified WOG methodology can directly reflect plant operational experiences by utilization of existing piping failure data.

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