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Development of Phased Mission Analysis Program with Monte Carlo Method

—Improvement of the variance reduction technique with biasing towards top event—

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Development of Phased Mission Analysis Program with Monte Carlo Method -Improvement of the variance reduction technique with Biasing towards Top Event -

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Abstract

This report presents a variance reduction technique to estimate the reliability and availability of highly complex systems during phased mission time using the Monte Carlo simulation. In this study, we introduced the variance reduction technique with a concept of distance between the present system state and the cut set configurations. Using this technique, it becomes possible to bias the transition from the operating states to the failed states of components towards the closest cut set. Therefore a component failure can drive the system towards a cut set configuration more effectively.

JNC developed the PHAMMON (Phased Mission Analysis Program with Monte Carlo Method) code which involved the two kinds of variance reduction techniques : (1) forced transition, and (2) failure biasing. However, these techniques did not guarantee an effective reduction in variance. For further improvement, a variance reduction technique incorporating the distance concept was introduced to the PHAMMON code and the numerical calculation was carried out for the different design cases of decay heat removal system in a large fast breeder reactor. Our results indicate that the technique addition of this incorporating distance concept is an effective means of further reducing the variance.

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モンテカルロ法によるフェイズドミッション解析プログラムの開発
ー頂上事象成立バイアス法の採用による分散低減手法の改良ー

楊　錦安 *,1)、三原　隆嗣 *

要旨

成功基準が時間と共に変化するシステムの信頼度をより現実的に評価することを目的として、使命時間を複数のフェイズに分割して評価を行うフェイズドミッション解析コード：PHAMMONの開発を行っている。大規模なシステムモデルにも適用可能とするためモンテカルロ法を採用しており、既に強制遷移法と故障バイアス法という２種類の分散低減法を取り入れている。しかしながら、評価対象によってはこれらの方法のみでは分散低減の度合が不十分な場合もあり、本研究ではさらなる改良を目的として、頂上事象成立バイアス法を適用した計算アルゴリズムの改良を行った。

頂上事象成立バイアス法では、任意のシステム状態から各々のカットセット成立状態までの遷移の起こりやすさを指標化した「遷移距離」を計算し、機器の運転成功から故障状態への状態遷移のサンプリングを「遷移距離」の最も短いカットセット成立に向けてバイアス（偏向）させることにより、カットセットが成立する有効ヒストリーをより効率的に発生させようとするものである。

上述の頂上事象成立バイアス法をPHAMMONコードに導入し、大型高速増殖炉モデルプラントの崩壊熱除去系を評価例として適用計算を実施した。その結果、本方法はモンテカルロ法による出力結果の分散をさらに低減する上で有効であるとの結論を得た。

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1. Introduction

In the past twenty years, much attention has been paid to probabilistic safety assessment (PSA) in nuclear safety community. At present, the useful insights which derived from PSA studies have had a significant impact on the design and operation of complex systems such as Nuclear Power Plants.

Monte Carlo simulation of Markov processes offers a potentially powerful tool for the evaluation of the reliability and availability of highly complex systems such as systems with long mission times, e.g., decay heat removal system in liquid metal fast breeder reactors (LMFBRs) where success criteria and grace periods are given as a function of time due to decrease of decay heat. In order to take these effects into account and to perform more realistic analysis, it is necessary to divide mission time into some phases. The Phased Mission Analyses Program with Monte Carlo method - PHAMMON code[1] was developed by Japan Nuclear Cycle Development Institute(JNC) using Monte Carlo method to analyze a Markov transition process with phased mission time; it has been applied to reliability analysis for decay heat removal system of a large LMFBR. The main steps on treating one history in PHAMMON code is depicted in Fig.1.1.

In applying the Monte Carlo method to practical problems, numerical values can be obtained. This usually involves an estimate of the statistical errors in those values. We can evaluate these statistical errors by using the Central Limit Theorem, which is described as: let $\bar{X}_n$ denote the mean of a random sample of size n from a distribution that has mean μ and positive variance σ^2 , then the random variable $Y_n = \sqrt{n}(\bar{X}_n - \mu)/\sigma$ has an approximate normal distribution with mean zero and variance 1.

From the Central Limit Theorem, we can obtain

$$P(Y_n < X_\alpha) \to \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x_\alpha} e^{-\frac{1}{2}x^2} dx \quad ...... \quad (1)$$

For $\forall\, X_\alpha > 0$,

$$P(|Y_n| < X_\alpha) = P(|\bar{X}_n - \mu| < \frac{X_\alpha \cdot \sigma}{\sqrt{n}}) \approx \frac{2}{\sqrt{2\pi}} \int_0^{X_\alpha} e^{-\frac{1}{2}x^2} dx = 1 - \alpha \quad ...... \quad (2)$$

It means the random interval $(\bar{X}_n - X_\alpha \cdot \sigma / \sqrt{n}\ , \bar{X}_n + X_\alpha \cdot \sigma / \sqrt{n})$ includes the mean μ with a probability of $(1-\alpha)$. In another word, the error for Monte Carlo estimate is $\varepsilon = X_\alpha \cdot \sigma / \sqrt{n}$, where X_α equals 1.96 or 3 , while α equals 0.05 or 0.01, respectively.

This implies that the statistical error can be decreased by increasing total history number n or reducing variance σ^2. The difficulty becomes apparent if we simply increase the number of histories. This is because $\bar{X}_n$ converges to the exact value μ with a speed of $O(n^{-\frac{1}{2}})$ quite slowly.

Moreover, in PSA of real systems it usually happens that: (i) the mean time to failure of component is much longer than the mission time; (ii) the mean time to repair of failed component is much shorter than the mission time. Consequently, a cut set rarely occurs. In the direct Monte Carlo method, only a very small fraction of the histories will contribute to the unreliability tally. As a result, the variance will tend to be large unless an exceedingly large number of histories is simulated. Therefore, suitable variance reduction techniques are almost mandatory.

The PHAMMON code has a Monte Carlo method with variance-reducing techniques[2] in order to decrease the variance of the Monte Carlo estimates of the reliability. However, There was no guarantee that the methods always reduce the variance.

M. Marseguerra and E. Zio[3] proposed a dependency model in which a system consists of various components, and each has many possible states. To solve this dependency model, a variance reduction method was also provided. The method allowed us to favour not only the failures, but also, among failures, to favour those transitions leading towards the top event. Numerical results show that this method is highly effective.

In order to further reduce the variance of the result from the PHAMMON code execution, we decided to introduce the idea proposed by M.Marseguerra and E.Zio. In this study, first, we modified the method suitable for the PHAMMON code; second, proposed a new definition of the distance which can be interpreted as the possibility of the transition from present state to cut set configuration; finally, we applied these methods to the PHAMMON code. In our analyses, we provide a comparison among the original PHAMMON code method, the method incorporating the distance definition of M. Marseguerra and E. Zio and a new method incorporating the distance definition we created.

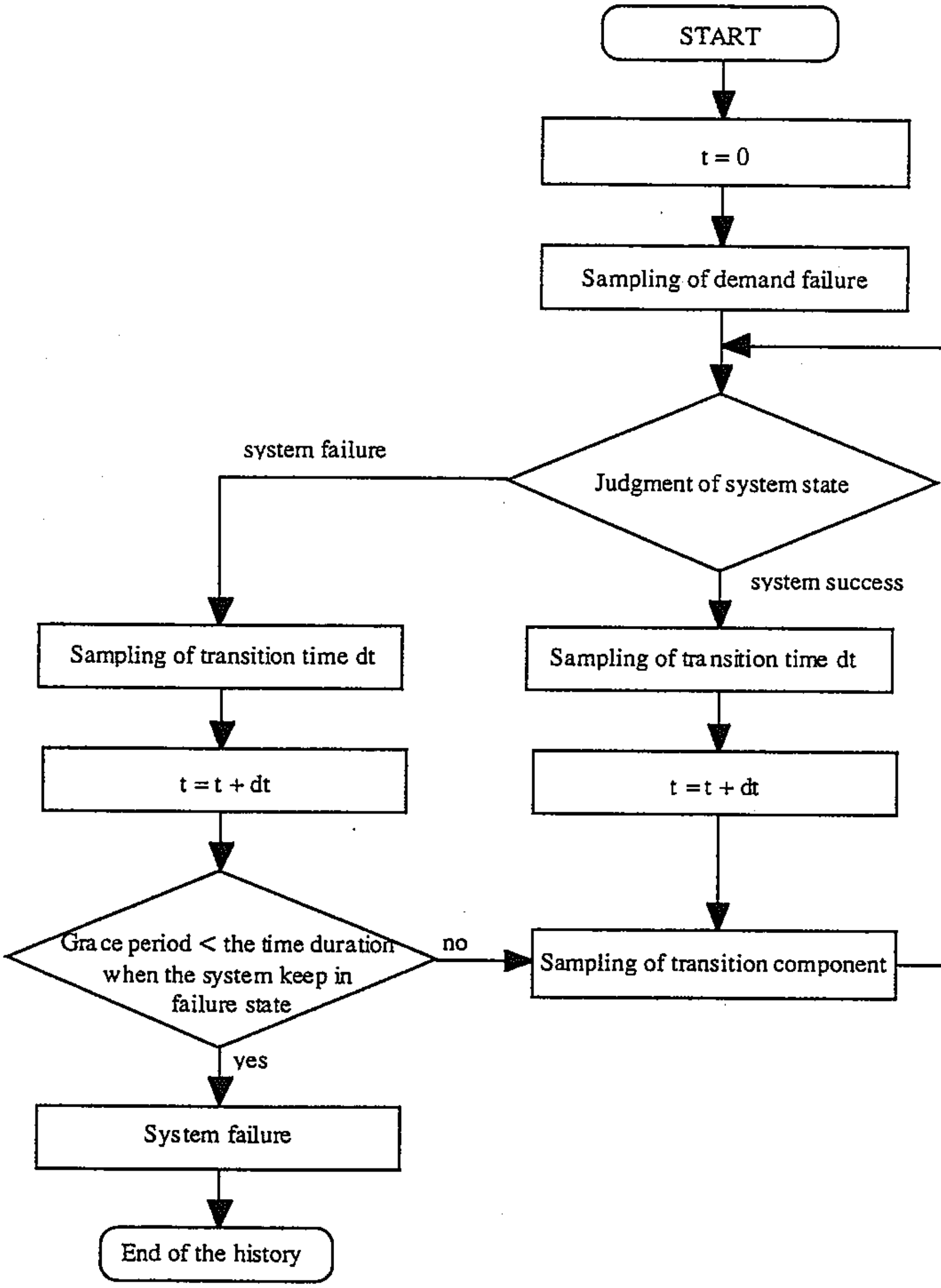

Fig.1.1 Flowchart for one history

2. Methods of Biasing

In this section, first, we briefly review the sampling method adopted in the PHAMMON code, then describe the biasing method of the transitions towards the closest cut set.

The PHAMMON code had employed two techniques, which were referred to as forced transition and failure biasing. In these two methods, the sampling distributions are modified, first, to produce an artificially large number of component transitions, and second, to increase the ratio of failures to repairs. Each trial is attached with a weight, initialized to 1, then, the weight is modified appropriately each time when a biased sampling distribution is used. By defining weighted tallies, the results are shown as unbiased estimators .

2.1 Forced transition

Considering a system made of **n** independent components, each of which may be either operating or failed. Then there are 2^n system states arising from all possible combinations of operating and failed components, and all possible transitions of the systems can be divided into two classes , namely N, and F.

1) If a transition corresponds to a component repair, then it belongs to N , i.e. it represents a return to the operating state from the failed state.

2) If a transition corresponds to a change from the operating state to the failed state which is a basic event for one or more cut sets, then it belongs to F.

In forced transitions, the probability density function that a system in state k' at time t' will make a state transition at time **t** is modified by

$$\tilde{f}(t/t',k') = \frac{\gamma_{k'} e^{-\gamma_{k'}(t-t')}}{1-e^{-\gamma_{k'}(T-t')}} \quad ...... (3)$$

where $\gamma_{k'}$ is the sum of the failure rates of the functional components and the repair rates of the failed components and T is the mission time. With this the uniformly distributed random variable ξ' can be used to sampling the interval to the next transition:

$$\Delta t = -\frac{1}{\gamma_{k'}} \ln(1-\xi'(1-e^{-\gamma_{k'}(T-t')})) \qquad 0 \le \Delta t \le T-t' \quad ...... (4)$$

and causing the next transition to be forced before the end of mission time. In order to compensate for the modified sampling, the trial weight is modified by

$$w \rightarrow w[1 - e^{-\gamma_{k'}(T - t')}] \quad ...... \quad (5)$$

2.2 Failure biasing

In failure biasing, the transition probabilities are modified to increase the ratio of failures to repairs.

Now consider the component **i** with a failure rate λ_i and a repair rate μ_i , then, the total transition rate is :

$$\Sigma = \Sigma_\mu + \Sigma_\varphi \quad ...... \quad (6)$$

where

$$\Sigma_\mu = \sum_{i \in N} \mu_i \quad ...... \quad (7)$$

$$\Sigma_\varphi = \sum_{i \in F} \lambda_i \quad ...... \quad (8)$$

To bias the different classes of the transitions, the interval (0, 1) is divided into two subintervals by introducing the parameters $0 \le X < 1$. Let $\boldsymbol{k'}$ be the state vector representative of the system before the transition and $\boldsymbol{k}$ the new state vector.

Determination of which component has failed or been repaired, and thereby of the new state of the system , is carried out as follows:

A random number ξ is first generated.

If $\xi < X$, the transition belongs to **F** and the failure component **i** is determined from

$$\sum_{\substack{i'=1 \\ i' \in F}}^{i-1} \lambda_{i'} \le \frac{\xi}{X} \cdot \Sigma_\varphi < \sum_{\substack{i'=1 \\ i' \in F}}^{i} \lambda_{i'} \quad ...... \quad (9)$$

and the weight is multiplied by the ratio of the unbiased probability $q(k / k') = (\lambda_i / \Sigma)$ to biased probability $\tilde{q}(k / k') = (\lambda_i / \Sigma_\varphi) \cdot X$, viz.

$$\frac{q(k/k')}{\tilde{q}(k/k')} = \frac{1}{X} \cdot \frac{\Sigma_\varphi}{\Sigma} \quad \text{......} \ (10)$$

If $\xi \geq X$, the transition belongs to N and the repaired component **i** is determined from

$$\sum_{\substack{i'=1 \\ i' \in N}}^{i-1} \mu_{i'} \leq \frac{\xi - X}{1 - X} \cdot \Sigma_\mu < \sum_{\substack{i'=1 \\ i' \in N}}^{i} \mu_{i'} \quad \text{......} \ (11)$$

and the weight is multiplied by the ratio of the unbiased probability $q(k/k') = (\mu_i / \Sigma)$ to biased probability $\tilde{q}(k/k') = (\mu_i / \Sigma_\mu) \cdot (1 - X)$, viz.

$$\frac{q(k/k')}{\tilde{q}(k/k')} = \frac{1}{(1-X)} \cdot \frac{\Sigma_\mu}{\Sigma} \quad \text{......} \ (12)$$

In using these variance reduction techniques, the weight is appropriately modified at each biased sampling until the first system failure occurs.
The estimate for the unavailability is

$$\bar{X}_m = \frac{\sum^{n_m} w_k}{N} \quad \text{......} \ (13)$$

the sample variance is given by

$$\sigma_m^2 = \frac{1}{N-1} \cdot \frac{\sum^{n_m} (w_k - \bar{X}_m)^2}{N} \quad \text{......} \ (14)$$

and the **f.s.d** (fractional standard deviation) is then

$$f.s.d = \sqrt{\sigma_m^2} / \bar{X}_m \quad \text{......} \ (15)$$

where

N : the total history number

n_m : the effective history number

w_k : the weight for **k**th effective history

2.3. Biasing of the transitions towards the closest cut set

Although with the improved sampling in the PHAMMON code, only very rare trial contributed a nonzero tally, in the case of highly reliable system, one of the reason is that a component failure sampling does not necessarily drive the system towards a cut set configuration which is more probable failure. In order to further increase the computational efficiency for highly reliable systems, here we introduce another variance reduction method when sampling the failed component , and the method is referred to as biasing of the transitions towards the closest cut set . The details are as follows:

First , sampling a random number ξ uniformly distributed in (0,1).

If $\xi \geq X$, the transition belongs to N, and sampling for transition component is performed in the same way as eq(9) and eq(10) in previous section.

when $\xi < X$, the transition belongs to F, i.e. the new state represents a basic event for a cut set. In order to select a cut set among the possible ones, for each cut set we introduce a distance from the present configuration and try to favour the closer ones. This distance should not be intended in a strict mathematical sense, but rather as a utility tool to be defined according to appropriate rules: the smaller number for transitions to reach the cut set N_n and the more probable $\psi_n^l / \Sigma_\varphi$ they are, then the closer that configuration of the cut set is. In terms of the idea proposed by M. Marseguerra and E. Zio, the distance can be described as:

$$D_n = N_n \sum_{l=1}^{N_n} \frac{1}{\psi_n^l / \Sigma_\varphi} \qquad n = 1,2, \ldots ,N_{cs} \quad \ldots\ldots \quad (16)$$

where

N_{cs} : the number of cut sets of any order of the system .

N_n : the minimum number of the transitions from the present configuration to the nth cut set configuration (CS_n) .

ψ_n^l , $l = 1, \ldots , N_n$ denote the transition rate λ_i , suitably renamed, which lead to the configuration CS_n. Note that each of these transitions may contribute to more than one cut set .

In order to select a cut set which effectively drives the system towards failure, the probability interval (0, X) is divided in N_{cs} subintervals of width

$$p_n = \frac{1/D_n}{\sum_{j=1}^{N_{cs}} 1/D_j} \cdot X \qquad n = 1,2, \ldots ,N_{cs} \quad \ldots\ldots \quad (17)$$

Then the largest subinterval belongs to the closest cut set.
The transition occurs leading to nth cut set for which

$$\sum_{n'=1}^{n-1} p_{n'} \leq \xi < \sum_{n'=1}^{n} p_{n'} \quad \ldots\ldots \quad (18)$$

Now we can select a transition among the N_n possible components. To this aim the subinterval p_n is further divided into N_n subintervals, corresponding to the N_n transitions.

$$p_n^l = \frac{\psi_n^l}{\psi_n} \cdot p_n \quad l = 1,2, \ldots ,N_n \quad \ldots\ldots \quad (19)$$

where $\psi_n = \sum_{l'=1}^{N_n} \psi_n^{l'}$.

The failure occurring is the one corresponding to the subinterval Z determined from

$$\sum_{n'=1}^{n-1} p_{n'} + \sum_{l'=1}^{l-1} p_n^{l'} \leq \xi < \sum_{n'=1}^{n-1} p_{n'} + \sum_{l'=1}^{l} p_n^{l'} \quad \ldots\ldots \quad (20)$$

Let us assume that the sampled transition changes the component Z to failed state. That is $\psi_n^l = \lambda_l$. For the evaluation of the weight, we should consider the fact that the sampled transition can draw the system closer not only to CS_n but also to some other cut set configurations CS_r , CS_s , ... which the same transition also appears in, say $p_r^{l_r} \in P_r$, $p_s^{l_s} \in P_s$,..... respectively. The weight is then multiplied by the ratio of the unbiased probability $q(k/k') = (\lambda_l/\Sigma)$ to the biased probability $\tilde{q}(k/k') = p_n^l + p_r^{l_r} + p_s^{l_s}$, viz.

$$\frac{q(k/k')}{\tilde{q}(k/k')} = \frac{\lambda_l/\Sigma}{p_n^l + p_r^{l_r} + p_s^{l_s} + \cdots}$$

$$= \frac{1}{X} \cdot \frac{\sum_{j=1}^{N_{cs}} \frac{1}{D_j}}{\left(\frac{1}{\psi_n \cdot D_n} + \frac{1}{\psi_r \cdot D_r} + \frac{1}{\psi_s \cdot D_s} + \cdots\right) \cdot \Sigma} \quad \cdots\cdots \quad (21)$$

The distance defined by eqn (16) seems to be based on the following idea : if we think $\psi_n^l / \Sigma_\varphi$ is a relative failure probability for a component which has the failure rate ψ_n^l, then the distance for a component can be defined as a reverse of relative failure probability, therefore the distance for a cut set can be obtained from the sum of the component distances and the less transitions to reach the cut set configuration. To apply the probability theory more directly, we can propose another definition of distance like below.

$$D_n = \prod_{l=1}^{N_n} \frac{1}{\psi_n^l \cdot T} \qquad n = 1, 2, \ldots, N_{cs} \quad \cdots\cdots \quad (22)$$

where N_{cs} , N_n , ψ_n^l are the same as illustrated in eq(16) and T is mission time. Our definition relies on the idea that with the more probability of reaching the nth cut set configuration, the shorter distance is assigned to nth cut set. The weight incorporating to the distance definition eq.(22) can be calculated by the same expression as described in eq.(21).

In the following section, we will compare the statistical efficiency of Monte Carlo method among the methods referred above through application to an LMFBR(Liquid-metal cooled fast breeder reactor) decay heat removal system reliability study.

3. Program Description

In the section 2, we described the new variance reduction technique. To apply this methodology, we modified the PHAMMON code. In this section , a flowchart on biasing the transitions towards the closest cut set and a description of input cards are presented.

3.1. Flowchart for biasing towards the closest cut set

The flowchart for biasing towards the closest cut set is shown in Fig.3.1.

3.2. Input description

In this section , we only have a short introduction of input, the more information is described in Ref.1 . Distinct from the original version, we added the method selection parameter which was used to decide the way for unreliability calculation. The cards are input in a fixed form and classed in seven categories. A brief description is as follows:

(A) System initial configuration

Input card A-1

Format : 9X, I1, 5D10.3

Input variable : NMPHSE, (PTIME(I), I = 1, NMPHSE)

where

NMPHSE ; number of phases

PTIME ; the end time for each phase

Input card A-2

Format : 5 (2A8)

Input variable : (EQ1(I), EQ2(I), I = 1, NMPHASE)

where

EQ1(I), EQ2(I) ; name of the minimal cut set equation on each phase

(B) Method selection for grace period calculation

Input card B-1

Format : I10

Input variable : IGR

where

IGR = 1, grace period is given for each phase

IGR = 2, grace period is calculated from linear function

IGR = 3, grace period is obtained from dynamic behavior

i) If IGR equals 1

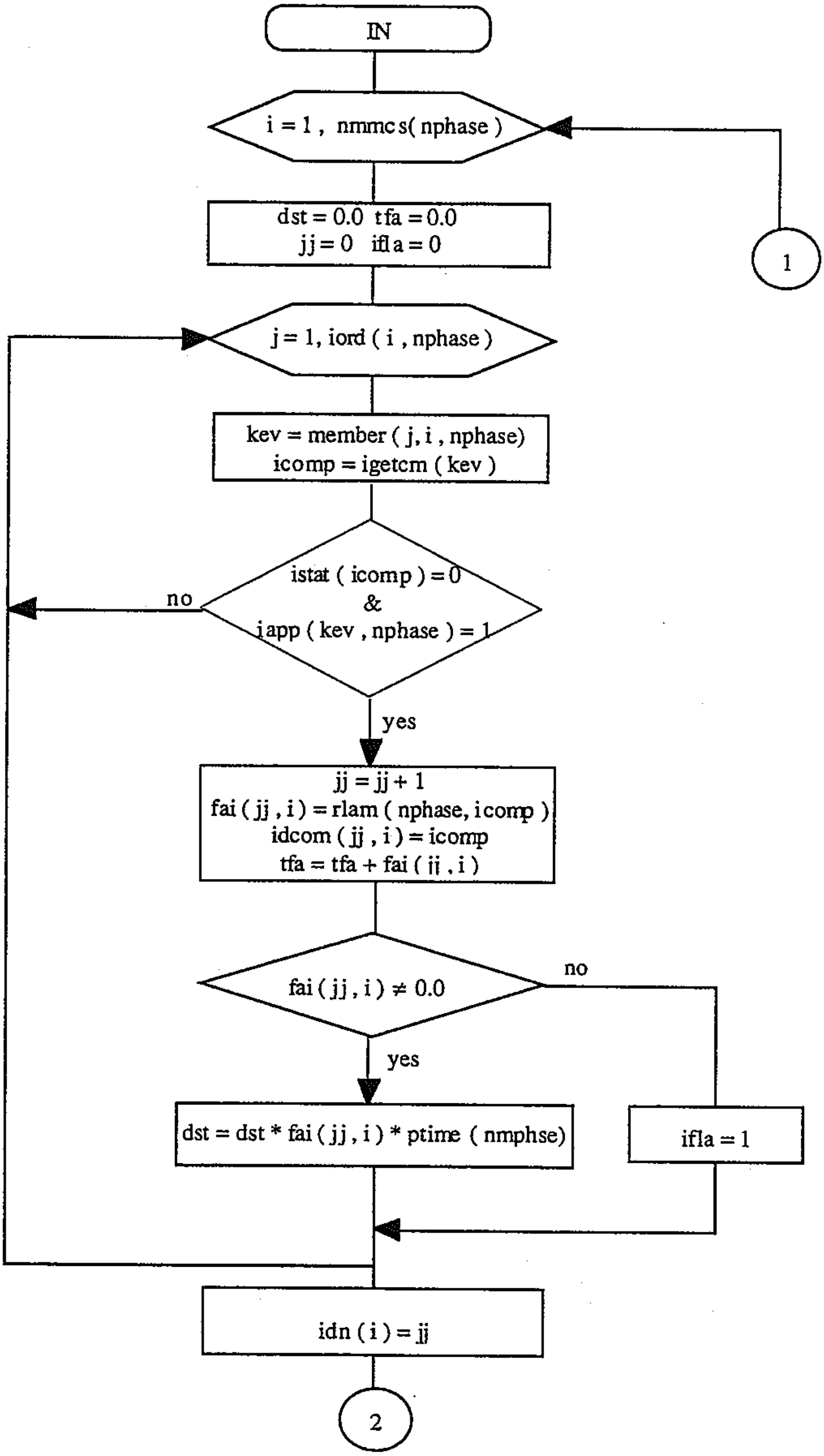

Fig. 3.1 Flowchart for biasing towards the closest cut set (1 / 4)

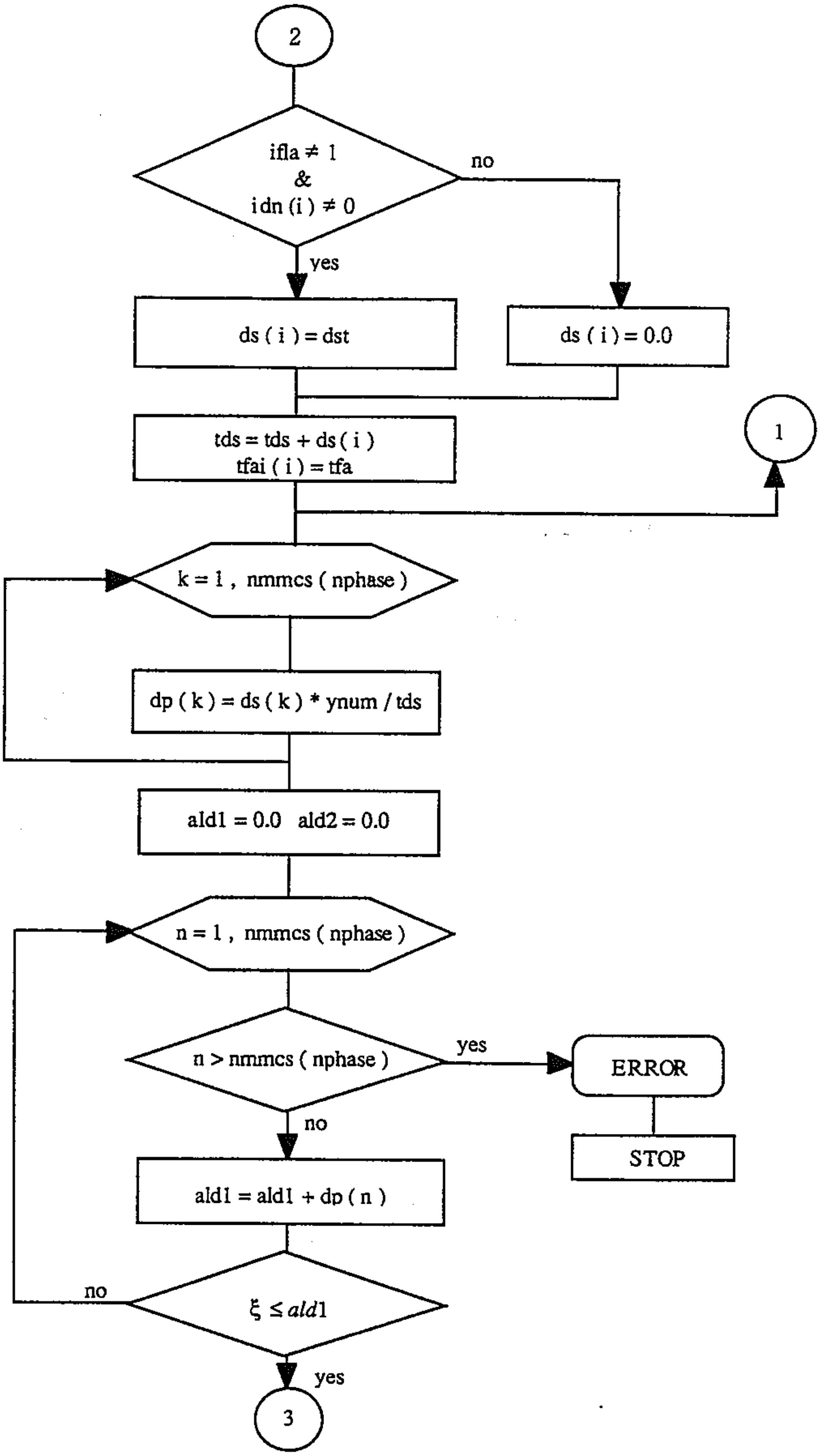

Fig. 3.1 Flowchart for biasing towards the closest cut set (2 / 4)

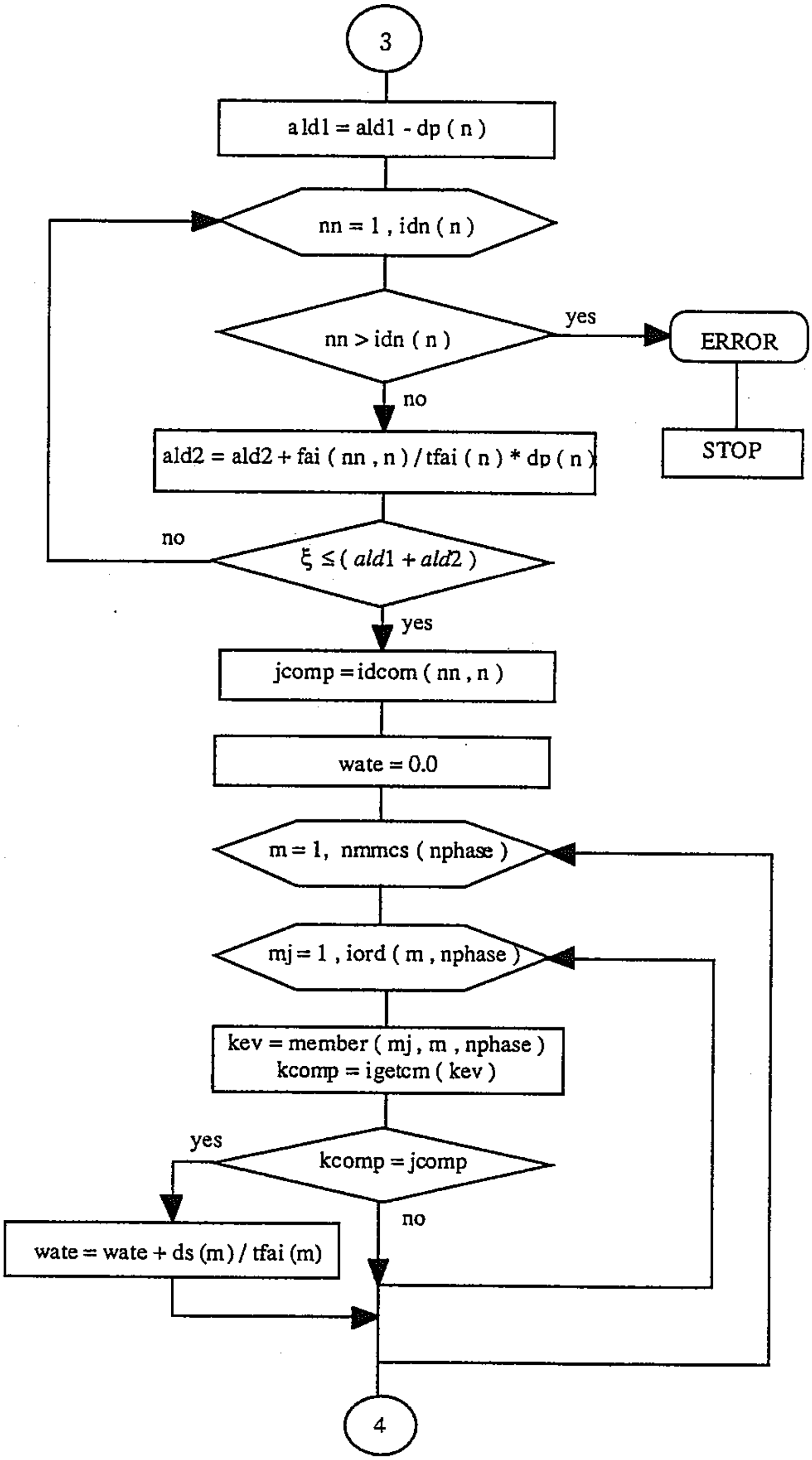

Fig. 3.1 Flowchart for biasing towards the closest cut set (3 / 4)

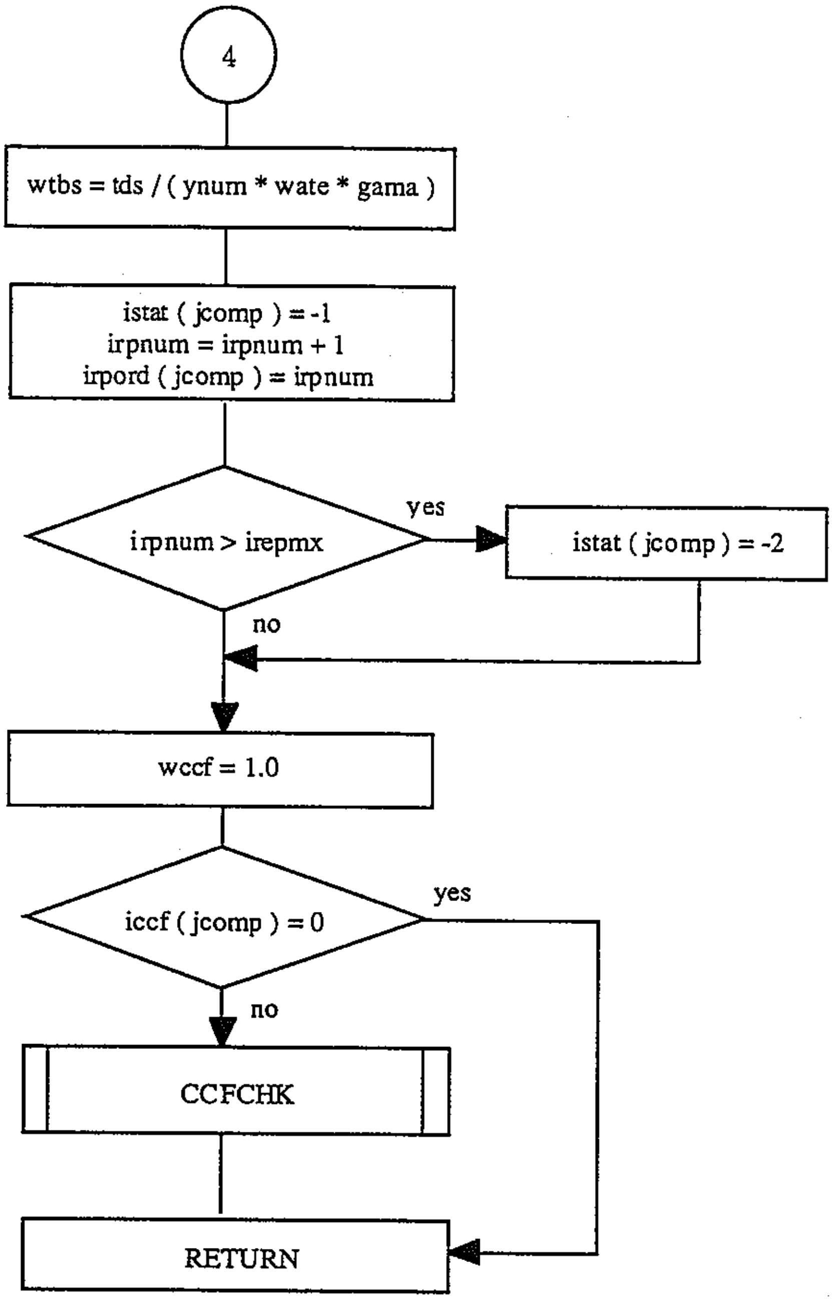

Fig.3.1 Flowchart for biasing towards the closest cut set (4 / 4)

Input card B-2

Format : 9X, I1, 5D10.3

Input variable : IAPHSE, (ATIME(I), I = 1, IAPHSE)

where

IAPHSE; number of the phases related to grace period

ATIME; the end time of each phase corresponding to the grace period

Input card B-3

Format : 5D10.3

Input variable : (GTIME(I), I = 1, IAPHSE)

where

GTIME ; grace time assigned on each phase

ii) If IGR equals 2

Input card B-2

Format : 2D10.3

Input variable : GRT1, GRT2

where

GRT1, GRT2; coefficients of linear function . grace time is calculated from linear function : TG(T) = GRT1 * T + GRT2

iii) If IGR equals 3

Input card B-2

Format : 8D10.3

Input variable : TEMP0, TEMPMX, CNA, (QR(I), I = 1, NMPHASE)

where

TEMP0 ; initial temperature

TEMPMX ; the superior limit of temperature

CNA ; total heat capacity

QR(I) ; heat removal capacity for each phase

Input card B-3

Format : I10

Input variable : ITINM

where

ITINM ; number of the data points, which is used to determine decay heat level

Input card B-4

Format : 2D10.3

Input variable : (TI(I), QD(I), I =1, ITINM)

where

TI(I) ; the time assigned on each point after reactor shutdown

QD(I) ; the decay heat rate at time TI(I)

(C) Method selection for variance reduction technique

Format : I10

Input variable : ISECM

where

ISECM = 1, LB method

ISECM = 2, biasing of the transitions towards the closest cut set

(D) Description of component parameters

Input card D-1

Format : COMPDATA

where

COMPDATA is a character variable, which denoted the start of input data for component parameters.

Input card D-2

Format : 2A8, I3, I1, D10.0, 2(D8.0, F5.0), 8X, 2D8.0

Input variable : COMNAM(1,I), COMNAM(2,I), ICCF(I), MPHASE(I), RTIME(1,I), RLAM(1,I), RLAMEF(1,I), RMU(1,I), RMUEF(1,I), RBETA(1,I), XCCF(I)

where

COMNAM(1,I), COMNAM(2,I); component name

ICCF(I); a flag indicated if the component is related to common cause failure(CCF).

ICCF(I) = 0, CCF will not consider

ICCF(I) ≠ 0, CCF occured in the same ICCF(I)

MPHASE(I); number of phases used for defining component data

RTIME(1,I); the end time of phase 1

RLAM(1,I); component failure rate λ in phase 1

RLAMEF(1,I); error factor of failure rate λ

RMU(1,I); component repair rate μ in phase 1

RMUEF(1,I); error factor of repair rate μ

REBETA(I); β factor for the same ICCF(I) component

XCCF(I); biasing parameter for CCF sampling

If MPHASE(I) > 1, for phase 2 to phase MPHASE(I), component datas are as follows:

Input card D-3

Format : 20X, D10.0, 2(D8.0, F5.0)

Input variable : (RTIME(II,I), RLAM(II,I), RLAMEF(II,I), RMU(II,I), RMUEF(II,I), II =2, MPHASE(I))

where

RTIME(II,I); the end time of phase II

RLAM(II,I); component failure rate λ in phase II

RLAMEF(II,I); error factor of failure rate λ

RMU(II,I); component repair rate μ in phase II

RMUEF(II,I); error factor of repair rate μ

Input card D-4

Format : END

where

END is a character variable, which denoted the terminal of input data for component parameters.

(E) Calculation control parameters

Input card E-1

Format : 2I10, 4D10.3, I10

Input variable : IHTMX, ITRMX, XNUM, TMMX, TMCT, WTCT, IRAOF

where

IHTMX; history number

if IHTMX > 0, then IHTMX is the number of effective history ;

if IHTMX < 0, then ABS(IHTMX) is the number of total history .

ITRMX; maximum transition number for one history

XNUM; biasing value for variance reduction method

TMCT; time cutoff value

WTCT; weight cutoff value

IRAOF; initial value for random number generation

Input card E-2

Format : D10.3, 6I10

Input variable : Y, IREPMX, (IOHIST(I), I = 1, 5)

where

Y; a parameter used to decide transition ratio; generally, Y is null and it means forced transition.

IREPMX; maximum number of repairable component at same time

IOHIST(I); effective history ID number for recording the transition scheme

(F) Output control parameters

Format : 2I10, 9X, I1

Input variable : IBCMX, IHGMX, IPLOSW

where

IBCMX; batch number for MORSE method

IHGMX; number of the time points, for each point, unreliability will be evaluated

IPLOSW; variable related to the graph plotting function; usually, it is zero.

(G) Description of demand failure rate

Format : 20X, 6D10.3

Input variable : (DEMVAL(I,J), J =1, 5), XDEM(I)

where

DEMVAL(I,J); demand failure rate for each phase

XDEM(I); biasing value for demand failure sampling

There are some limitations in the PHAMMON code. The following are the details:

1) Maximum number of phases is 5;
2) Maximum number of components is 1000;
3) Maximum number of terms of minimal cut set is 10000;
4) Maximum number of orders for each term of minimal cut set is 6;
5) Maximum batch number of MORSE method is 20;
6) Maximum number of the time points for unreliability calculation is 50.

4. Case Study

To evaluate the performance of the new variance reduction method, following cases related to the decay heat removal system of an LMFBR were considered.

4.1 Initial case of decay heat removal system

4.1.1 Decay heat removal system[4]

The decay heat removal system , shown in Fig.4.1, consists of three-loop Intermediate Reactor Auxiliary Cooling System (IRACS) and one Direct Reactor Auxiliary Cooling System (DRACS) which provide a heat sink for the reactor core following reactor shutdown. The IRACS system can function in either of two modes, forced circulation (FC) and natural circulation(NC). But for DRACS system, only forced circulation mode is available.

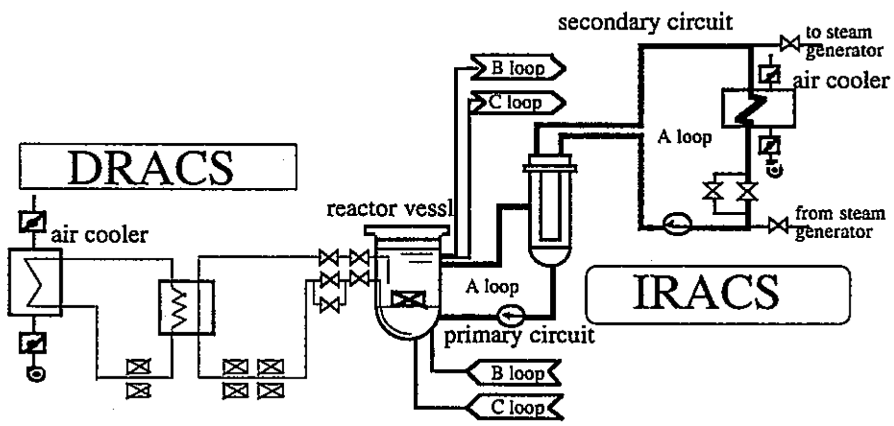

Fig.4.1 Decay heat removal system

4.1.2 Success criteria for initial case

Decay heat removal function appears in the event tree heading as one of the front line systems. According to the original design information , success criteria of the decay heat removal system were defined as follows (Table 4.1).

Table 4.1 success criteria of the decay heat removal system

phase	time after reactor shutdown [hr]	success criteria
1	0 - 1	1 loop IRACS FC or 3 loop IRACS NC
2	1 - 24	1 loop IRACS FC or 1 loop IRACS NC
3	24 - 168	1 loop IRACS FC or 1 loop IRACS NC or DRACS FC

These success criteria are applicable to the case in which all of the decay heat removal mode is available at just after reactor shutdown. Number of the available loop and its heat removal mode depend on the initiating events. To support the detailed system modeling, the system success criteria must be further translated to a statement defining the criteria for system failure. After considering the dependency on the initiating events, five kinds of failure criteria (D1 to D5) were developed shown in the Table 4.2.

4.1.3 Minimal cut sets corresponding to failure criteria

We assume that the minimal cut sets for 1 loop IRACS FC, 1 loop IRACS NC and DRACS FC are given below:

(1) 1 loop IRACS FC ;

AFCFAIL=AFC+AFNNR+AFNRC
+EPSA+CCA+OSP*DGA+CCPSA01*BTPSA+UPSA01.

BFCFAIL=BFC+BFNNR+BFNRC
+EPSB+CCB+OSP*DGB+CCPSB01*BTPSB+UPSB01.

CFCFAIL=CFC+CFNNR+CFNRC
+EPSC+CCC+OSP*DGC+CCPSC01*BTPSC+UPSC01.

(2) 1 loop IRACS NC ;

ANCFAIL=ANC+AFNNR+AFNRC+BTPSA*(EPSA+CCPSA01+OSP*DGA)
+UPSA01.

BNCFAIL=BNC+BFNNR+BFNRC+BTPSB*(EPSB+CCPSB01+OSP*DGB)
+UPSB01.

CNCFAIL=CNC+CFNNR+CFNRC+BTPSC*(EPSC+CCPSC01+OSP*DGC)
+UPSC01.

(3) DRACS FC ;

DFAIL=MCSFC+(EPSA+CCA+OSP*DGA+CCPSA01*BTPSA+UPSA01)
*(EPSC+CCC+OSP*DGC+CCPSC01*BTPSC+UPSC01).

The macro events used above were defined as shown in Table 4.3.

Table 4.2 Failure criteria of the Case 1

D1: All loops are available

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	3 loop IRACS FC and 1 loop IRACS NC
2	1 - 24	3 loop IRACS FC and 3 loop IRACS NC
3	24 - 168	3 loop IRACS FC and 3 loop IRACS NC and DRACS FC

D2: Neither FC nor NC are available for one IRACS loop

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	2 loop IRACS FC
2	1 - 24	2 loop IRACS FC and 2 loop IRACS NC
3	24 - 720	2 loop IRACS FC and 2 loop IRACS NC and DRACS FC

* The mission time is 720 hr.

D3: Only FC are unavailable for one IRACS loop

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	2 loop IRACS FC and 1 loop IRACS NC
2	1 - 24	2 loop IRACS FC and 3 loop IRACS NC
3	24 - 168	2 loop IRACS FC and 3 loop IRACS NC and DRACS FC

D4: Loss of off-site power

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	3 loop IRACS FC and 1 loop IRACS NC
2	1 - 24	3 loop IRACS FC and 3 loop IRACS NC
3	24 - 168	3 loop IRACS FC and 3 loop IRACS NC and DRACS FC

* at t = 0, off-site power(corresponding event is 'OSP') is fail with probability of 1.0.

D5: DRACS is unavailable

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	3 loop IRACS FC and 1 loop IRACS NC
2	1 - 168	3 loop IRACS FC and 3 loop IRACS NC

Table 4.3　　Macro events and its reliability parameter

※ 1　;Loss of function of XXX' means a system or one train XXX failure due to a failure of component which belongs to only XXX, not to support system of XXX.

※ 2　'X' means the kind of loop or train .

※ 3　a macro event covered by [shaded box] means that this macro event is sum of the other macro events.

※ 4　XFN＝XFNNR＋XFNRC

※ 5　used in only case 4

macro event (※2) (※3)	demand failure rate [/demand]	running failure rate [/hour]	event description (※ 1)
XFC01	2.3E-3	1.1E-4	A set of events which result in only FC(forced circulation) mode failure in ACS X train. The events in this set are related to failure of the components included in only ACS X train(primary loop X, secondary loop X, and ACS X) .
PMCS X	2.1E-3	1.8E-5	Loss of function of the primary loop X pony motor cooling system
XSGMOV12	6.9E-7	4.9E-8	Fail to close both the SG(steam generator) inlet stop valve and the SG outlet stop valve in secondary loop X.
XFC	4.4E-3	1.2E-4	A set of events which result in only FC(forced circulation) mode failure in ACS X train.(AFC+PMCSA+ASGMOV12)
XFN01	5.7E-3	3.1E-5	A set of events which result in both FC and NC(natural circulation) mode failure in ACS X train. The events in this set are related to failure of the components included in only ACS X train(primary loop X, secondary loop X, and ACS X) .
XACMOV1	8.3E-4	8.3E-6	Fail to open the ACS outlet stop valve in ACS X train
XFN	6.5E-3	3.9E-5	A set of events which result in both FC and NC mode failure in ACS X train. (XFN01+XACMOV1)
XFNNR (※4)	1.3E-5	7.1E-6	A set of events which result in both FC and NC mode failure in ACS X train and is assumed to be not repairable.
XFNRC (※4)	6.5E-3	3.2E-5	A set of events which result in both FC and NC mode failure in ACS X train and is assumed to be repairable.
CCS X	4.6E-4	1.1E-4	Loss of function of the CCS(component cooling system) x train
CCWS X	2.6E-5	3.1E-5	Loss of function of the CCWS(component cooling water system) x train
CCX	4.8E-4	1.5E-4	Loss of function of either the CCS x train or CCWS x train

macro event (※2) (※3)	demand failure rate [/demand]	running failure rate [/hour]	event description (※1)
EPS X 01	1.1E-5	2.2E-5	Loss of function of either the 6.6kV M/C(metal-clad switch gear) X train or the 440V P/C (power center) X train
CSSS X	2.7E-5	3.1E-5	Loss of function of the CSSS(component sea water supply system) X train
HVAC X	1.9E-4	4.7E-5	Loss of function of the HVAC(heating ventilation and air conditioning system) X train for electrical power equipment room
CHILLER X	4.2E-5	5.9E-5	Loss of function of the chiller system X train for HVAC
EPS X	2.7E-4	1.6E-4	A set of the events which result in loss of electrical power supply function from either the 6.6kV M/C(metal-clad switch gear) X train or the 440V P/C (power center) X train (EPS X 01+CSSS X+HVAC X+CHILLER X)
MCSFC01	6.8E-3	6.6E-5	A set of events which result in FC(forced circulation) mode failure in MCS(maintenance cooling system). The events in this set are related to failure of the components included in only MCS.
EMPCS	6.3E-3	3.3E-5	Loss of function of the MCS EMP(electromagnetic pump) cooling system.
MCSFC	1.3E-2	9.8E-5	A set of events which result in FC mode failure in MCS.(MCSFC01+EMPCS)
MCSFC (※5)	7.4E-3	9.8E-5	A set of events which result in only FC mode failure in MCS.
MCSFNNR (※5)	2.8E-5	6.8E-6	A set of events which result in both FC and NC mode failure in MCS and is assumed to be no repairable.
MCSFNRC (※5)	5.7E-3	2.4E-5	A set of events which result in both FC and NC mode failure in MCS and is assumed to be repairable.
OSP	1.4E-5	3.7E-5	Loss of off-site power (loss of electrical power supply from off-site to 6.6kV M/C).
DG X	1.4E-2	2.4E-4	Loss of electrical power supply from the emergency diesel generator train X to 6.6kV M/C train X
BTPS X	2.1E-5	4.1E-5	Loss of electrical power supply from the battery train X to the 110V AC vital power supply system train X
CCPS X 01	1.5E-5	3.0E-5	Loss of function of the 440V C/C (control center) X train
UPS X 01	7.9E-6	1.6E-5	Loss of function of the 110V AC vital power supply system train X

After these minimal cut sets data have been derived, the minimal cut set equation for each failure criteria defined in previous section can be formed by substituting the equations for 1 loop IRACS FC , 1 loop IRACS NC and DRACS FC into the below Boolean equations and simplifying with Boolean calculation.

For case D1, we assume that all loops are available and the Boolean equations for each phase are as follows.

phase1(3 loop IRACS FC and 1 loop IRACS NC)
3F1N
=(AFCFAIL*BFCFAIL*CFCFAIL)*(ANCFAIL+BNCFAIL+CNCFAIL).

phase2(3 loop IRACS FC and 3 loop IRACS NC)
3F3N
=(AFCFAIL*BFCFAIL*CFCFAIL)*(ANCFAIL*BNCFAIL*CNCFAIL).

phase3(3 loop IRACS FC and 3 loop IRACS NC and DRACS FC)
3F3N
=(AFCFAIL*BFCFAIL*CFCFAIL)*(ANCFAIL*BNCFAIL*CNCFAIL)*DFAIL.

For case D2, we assume that neither FC nor NC are available for one IRACS loop. To perform the PHAMMON code, we assign IRACS-B is unavailable. The following Boolean equations are obtained for each phase.

phase1(2 loop IRACS FC)
2F
=(AFCFAIL*CFCFAIL).

phase2(2 loop IRACS FC and 2 loop IRACS NC)
2F2N
=(AFCFAIL*CFCFAIL)*(ANCFAIL*CNCFAIL).

phase3(2 loop IRACS FC and 2 loop IRACS NC and DRACS FC)
2F2NM
=(AFCFAIL*CFCFAIL)*(ANCFAIL*CNCFAIL)*DFAIL.

For case D3 , we assume that only FC is unavailable for one IRACS loop; Loss of off-site power and DRACS is unavailable are the assumptions of the case D4 and D5, respectively. we can obtain minimal cut sets corresponding to each phase same as the case of D1 .

4.2 Sensitivity case of decay heat removal system

4.2.1 Case2 and Case3 (NC capacity up)

The success criteria (or failure criteria) described above is based on the original design and is called Case 1. In Case 1, the IRACS can successfully remove decay heat with three loops in natural circulation just after reactor shutdown. For Case2 and Case3 we assume 100% heat removal capacity of IRACS-NC can be attained by 2 loops or 1 loop, respectively. Based on the improvement of heat removal capacity, we developed failure criteria for Case2 and Case3 shown in the Table 4.4 and Table 4.5.

4.2.2 Case4 (DRACS capacity up)

In Case 4, heat removal capacity of IRACS-FC and NC are the same as in Case 1, and we assume natural circulation is available for DRACS, and DRACS can function as one of three loops of IRACS in both of the forced and natural circulation mode. Based on this assumption, we developed the failure criteria for Case 4 shown in the Table 4.6. Considering the ability of natural circulation mode, we modified the minimal cut sets for DRACS below.

DFCFAIL=MCSFC+MCSFNRC+MCSFNNR
+(EPSA+CCA+OSP*DGA+CCPSA01*BTPSA+UPSA01)
*(EPSC+CCC+OSP*DGC+CCPSC01*BTPSC+UPSC01).

DNCFAIL=MCSNC+MCSFNRC+MCSFNNR
+(BTPSA*(EPSA+CCPSA01+OSP*DGA)+UPSA01)
(BTPSC(EPSC+CCPSC01+OSP*DGC)+UPSC01).

4.3 Consideration on the system repairability

In order to study the effects of repair activity on system unreliability and unavailability calculation, we have chosen two kinds of special cases. first, to consider all of the components are unrepaired; second , for the component FNRC which can be repaired in both forced circulation and natural circulation mode, to improve the repair rate from 0.1 to 0.4 . Both of them will be considered in the initial Case 1.

Table 4.4 Failure criteria of the Case 2

D1: All loops are available

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	3 loop IRACS FC and 2 loop IRACS NC
2	1 - 24	3 loop IRACS FC and 3 loop IRACS NC
3	24 - 168	3 loop IRACS FC and 3 loop IRACS NC and DRACS FC

D2: Neither FC nor NC are available for one IRACS loop

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	2 loop IRACS FC and 1 loop IRACS NC
2	1 - 24	2 loop IRACS FC and 2 loop IRACS NC
3	24 - 720	2 loop IRACS FC and 2 loop IRACS NC and DRACS FC

* The mission time is 720 hr.

D3: Only FC are unavailable for one IRACS loop

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	2 loop IRACS FC and 2 loop IRACS NC
2	1 - 24	2 loop IRACS FC and 3 loop IRACS NC
3	24 - 168	2 loop IRACS FC and 3 loop IRACS NC and DRACS FC

D4: Loss of off-site power

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	3 loop IRACS FC and 2 loop IRACS NC
2	1 - 24	3 loop IRACS FC and 3 loop IRACS NC
3	24 - 168	3 loop IRACS FC and 3 loop IRACS NC and DRACS FC

* at t = 0, off-site power(corresponding event is 'OSP') is fail with probability of 1.0.

D5: DRACS is unavailable

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	3 loop IRACS FC and 2 loop IRACS NC
2	1 - 168	3 loop IRACS FC and 3 loop IRACS NC

Table 4.5 Failure criteria of the Case 3

D1: All loops are available

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	3 loop IRACS FC and 3 loop IRACS NC
2	1 - 24	3 loop IRACS FC and 3 loop IRACS NC
3	24 - 168	3 loop IRACS FC and 3 loop IRACS NC and DRACS FC

D2: Neither FC nor NC are available for one IRACS loop

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	2 loop IRACS FC and 2 loop IRACS NC
2	1 - 24	2 loop IRACS FC and 2 loop IRACS NC
3	24 - 720	2 loop IRACS FC and 2 loop IRACS NC and DRACS FC

* The mission time is 720 hr.

D3: Only FC are unavailable for one IRACS loop

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	2 loop IRACS FC and 3 loop IRACS NC
2	1 - 24	2 loop IRACS FC and 3 loop IRACS NC
3	24 - 168	2 loop IRACS FC and 3 loop IRACS NC and DRACS FC

D4: Loss of off-site power

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	3 loop IRACS FC and 3 loop IRACS NC
2	1 - 24	3 loop IRACS FC and 3 loop IRACS NC
3	24 - 168	3 loop IRACS FC and 3 loop IRACS NC and DRACS FC

* at t = 0, off-site power(corresponding event is 'OSP') is fail with probability of 1.0.

D5: DRACS is unavailable

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 168	3 loop IRACS FC and 3 loop IRACS NC

Table 4.6 Failure criteria of the Case 4

D1: All loops are available

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	(3 loop IRACS FC and DRACS FC) and (2 loop IRACS NC or 1 loop IRACS NC and DRACS NC)
2	1 - 168	3 loop IRACS FC and 3 loop IRACS NC and DRACS FC and DRACS NC

D2: Neither FC nor NC are available for one IRACS loop

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	(2 loop IRACS FC and DRACS FC) and (1 loop IRACS NC or DRACS NC)
2	1 - 720	2 loop IRACS FC and 2 loop IRACS NC and DRACS FC and DRACS NC

* The mission time is 720 hr.

D3: Only FC are unavailable for one IRACS loop

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	(2 loop IRACS FC and DRACS FC) and (2 loop IRACS NC or 1 loop IRACS NC and DRACS NC)
2	1 - 168	2 loop IRACS FC and 3 loop IRACS NC and DRACS FC and DRACS NC

D4: Loss of off-site power

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	(3 loop IRACS FC and DRACS FC) and (2 loop IRACS NC or 1 loop IRACS NC and DRACS NC)
2	1 - 168	3 loop IRACS FC and 3 loop IRACS NC and DRACS FC and DRACS NC

* at t = 0, off-site power(corresponding event is 'OSP') is fail with probability of 1.0.

D5: DRACS is unavailable

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	3 loop IRACS FC and 1 loop IRACS NC
2	1 - 168	3 loop IRACS FC and 3 loop IRACS NC

4.4 Consideration of decay heat removal capability with the water steam system

The failure probability of the decay heat removal system can be reduced if the redundancy of the decay heat removal system can be increased for the first 24 hours after reactor shutdown. Based on this proposal, we developed the decay heat removal system models with considering the heat removal capacity of the Water Steam System (WSS).

We assume that the minimal cut sets for the water steam system are as follows.
WSSSF = WSSS + OSP + ACSFCAW * ACSFCBW * ACSFCCW.
ACSFCAW = AFC + CCA + EPSA .
ACSFCBW = BFC + CCB + EPSB .
ACSFCCW = CFC + CCC + EPSC .
And another two cases related to WSS were considered.

4.4.1 Case5[5]

In the Case 5, heat removal capacity of IRACS FC, IRACS NC and DRACS FC are the same as in the Case 1, and we assume that the WSS can remove the decay heat alone for the first 24 hours. On the basis of this assumption, the failure criteria for the Case 5 were developed shown in the Table 4.7.

For case D1, we can get the minimal cut sets for each phase below.
phase1 (3 loop IRACS FC and 1 loop IRACS NC and WSSSF)
3F1NW
=(AFCFAIL * BFCFAIL * CFCFAIL) * (ANCFAIL + BNCFAIL + CNCFAIL) * WSSSF.

phase2 (3 loop IRACS FC and 3 loop IRACS NC and WSSSF)
3F3NW
=(AFCFAIL * BFCFAIL * CFCFAIL) * (ANCFAIL * BNCFAIL * CNCFAIL) * WSSSF.

phase3 (3 loop IRACS FC and 3 loop IRACS NC and DRACS FC)
3F3NM
=(AFCFAIL * BFCFAIL * CFCFAIL) * (ANCFAIL * BNCFAIL * CNCFAIL) * DFAIL.

For the case D2 to D5, the minimal cut sets can be obtained similar to the case of D1.

4.4.2 Case6

In the Case 6, we assume that heat removal capacity of IRACS FC, IRACS NC and DRACS FC are the same as in the Case 3, and the WSS can be used to remove the decay heat for the first 24 hours. Depending on this assumption, the failure criteria for the Case 6 were developed shown in the Table 4.8.

Table 4.7 Failure criteria of the Case 5
(Water steam system can remove the decay heat for the first 24 hours)

D1: All loops are available

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	3 loop IRACS FC and 1 loop IRACS NC and WSSSF
2	1 - 24	3 loop IRACS FC and 3 loop IRACS NC and WSSSF
3	24 - 168	3 loop IRACS FC and 3 loop IRACS NC and DRACS FC

D2: Neither FC nor NC are available for one IRACS loop

phase	time after reactor shutdown [hr]	2 failure criteria
1	0 - 1	2 loop IRACS FC and WSSSF
2	1 - 24	2 loop IRACS FC and 2 loop IRACS NC and WSSSF
3	24 - 720	2 loop IRACS FC and 2 loop IRACS NC and DRACS FC

* The mission time is 720 hr.

D3: Only FC are unavailable for one IRACS loop

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	2 loop IRACS FC and 1 loop IRACS NC and WSSSF
2	1 - 24	2 loop IRACS FC and 3 loop IRACS NC and WSSSF
3	24 - 168	2 loop IRACS FC and 3 loop IRACS NC and DRACS FC

D4: Loss of off-site power

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	3 loop IRACS FC and 1 loop IRACS NC
2	1 - 24	3 loop IRACS FC and 3 loop IRACS NC
3	24 - 168	3 loop IRACS FC and 3 loop IRACS NC and DRACS FC

* at t = 0, off-site power(corresponding event is 'OSP') is fail with probability of 1.0.

D5: DRACS is unavailable

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 1	3 loop IRACS FC and 1 loop IRACS NC and WSSSF
2	1 - 24	3 loop IRACS FC and 3 loop IRACS NC and WSSSF
3	24 - 168	3 loop IRACS FC and 3 loop IRACS NC

Table 4.8 Failure criteria of the Case 6
(Water steam system can remove the decay heat for the first 24 hours)

D1: All loops are available

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 24	3 loop IRACS FC and 3 loop IRACS NC and WSSSF
2	24 - 168	3 loop IRACS FC and 3 loop IRACS NC and DRACS FC

D2: Neither FC nor NC are available for one IRACS loop

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 24	2 loop IRACS FC and 2 loop IRACS NC and WSSSF
2	24 - 720	2 loop IRACS FC and 2 loop IRACS NC and DRACS FC

* The mission time is 720 hr.

D3: Only FC are unavailable for one IRACS loop

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 24	2 loop IRACS FC and 3 loop IRACS NC and WSSSF
2	24 - 168	2 loop IRACS FC and 3 loop IRACS NC and DRACS FC

D4: Loss of off-site power

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 24	3 loop IRACS FC and 3 loop IRACS NC
2	24 - 168	3 loop IRACS FC and 3 loop IRACS NC and DRACS FC

* at t = 0, off-site power(corresponding event is 'OSP') is fail with probability of 1.0.

D5: DRACS is unavailable

phase	time after reactor shutdown [hr]	failure criteria
1	0 - 24	3 loop IRACS FC and 3 loop IRACS NC and WSSSF
2	24 - 168	3 loop IRACS FC and 3 loop IRACS NC

5. Results and Discussion

In order to evaluate the effectiveness of the proposed variance reduction method which incorporate our definition for distance, we ran and compared the results of PHAMMON code simulations for the original PHAMMON code, the PHAMMON code revised to include the distance definition given by M.Marseguerra and E.Zio and the PHAMMON code incorporating our new definition for distance. For the remainder of this paper, These three methods are called the LB, ME and present work methods, respectively. Unless explicitly specified, all cases were performed with 10^5 trials and the failure biasing value for the unreliability calculation was set at $x = 0.85$. The computer used was a SUN Ultra Sparc 2.

Tables 5.1 - 5.8 compare the results of failure probability and errors(f.s.d) used by the LB method, ME method, and present work, while the computational times and ratios of effective history numbers are shown in Tables 5.9 - 5.16. Because the water steam system (WSS) can not function in the case of loss of off-site power, so we do not consider the failure criteria of D4 in studying the decay heat removal capability of the WSS.

As seen in Tables 5.1 - 5.16, both of the distance definitions lead to similar estimations of the failure probability and error for all cases, but compared with the ME method, our present work provides improvements both in saving CPU time and in increasing the effective history numbers. We can better explain the reason by considering a very simple system consisting of three independent components A, B and C with a failure rate of 10^{-4}/hr, 10^{-4}/hr and 10^{-5}/hr. If we assume the minimal cut set of the system is A * B + C, and the mission time is 100 hours, then we can easily know that using ME method, the second term C is sampled with an approximately probability of 30%, but for the present work method, the second term C can be sampled with probability increased of about 90%. It seems worth noting that second term C failure is much easier to reach compared with the first term A * B failure for a real case, as the probability to failure for C is 10^{-3} and A * B is 10^{-4} for 100 hours operation. In this sense, using the present work method, we can drive the system towards a cut set more efficiently without wasting time and histories.

We then continued the comparison between present work and LB method. the plots of f.s.d, versus time are shown in Figures 5.1 - 5.38.

Table 5.1 Results of the failure probability and f.s.d for Case 1

	LB method		ME method		Present work	
failure criteria	failure probability	f.s.d	failure probability	f.s.d	failure probability	f.s.d
case1_d1	6.492E-07	4.20%	6.606E-07	4.21%	6.743E-07	4.02%
case1_d2	9.520E-05	2.83%	1.010E-04	3.25%	9.725E-05	2.18%
case1_d3	5.591E-05	4.09%	6.008E-05	4.00%	5.888E-05	3.95%
case1_d4	1.730E-06	4.60%	1.877E-06	4.29%	1.765E-06	4.56%
case1_d5	7.064E-07	3.68%	7.151E-07	3.49%	7.193E-07	3.39%

Table 5.2 Results of the failure probability and f.s.d for Case 2

	LB method		ME method		Present work	
failure criteria	failure probability	f.s.d	failure probability	f.s.d	failure probability	f.s.d
case2_d1	3.498E-07	5.46%	3.572E-07	5.32%	3.788E-07	5.21%
case2_d2	7.380E-05	3.46%	7.544E-05	4.05%	7.259E-05	2.81%
case2_d3	1.811E-05	7.29%	1.796E-05	7.01%	1.676E-05	7.05%
case2_d4	5.665E-07	9.83%	4.891E-07	9.92%	5.960E-07	9.57%
case2_d5	3.680E-07	5.62%	3.782E-07	5.57%	3.657E-07	5.52%

Table 5.3 Results of the failure probability and f.s.d for Case 3

	LB method		ME method		Present work	
failure criteria	failure probability	f.s.d	failure probability	f.s.d	failure probability	f.s.d
case3_d1	8.241E-08	10.5%	7.998E-08	10.4%	8.955E-08	9.80%
case3_d2	2.885E-05	7.22%	3.758E-05	9.25%	3.149E-05	4.40%
case3_d3	1.110E-07	16.5%	7.586E-08	15.9%	9.792E-08	16.3%
case3_d4	9.610E-08	31.6%	8.058E-08	35.6%	1.050E-07	28.2%
case3_d5	9.650E-08	13.2%	1.001E-07	13.0%	9.757E-08	12.1%

Table 5.4 Results of the failure probability and f.s.d for Case 4

	LB method		ME method		Present work	
failure criteria	failure probability	f.s.d	failure probability	f.s.d	failure probability	f.s.d
case4_d1	1.193E-08	30.3%	1.128E-08	7.66%	9.100E-09	8.19%
case4_d2	6.590E-06	37.1%	5.319E-06	5.63%	4.181E-06	5.03%
case4_d3	5.258E-07	9.61%	5.633E-07	7.91%	5.320E-07	8.08%
case4_d4	1.587E-08	10.7%	2.177E-08	18.2%	1.945E-08	7.79%
case4_d5	1.156E-06	22.8%	1.072E-06	9.77%	1.040E-06	5.64%

Table 5.5 Results of the failure probability and f.s.d for unrepaired system

failure criteria	***LB method***		***ME method***		***Present work***	
	failure probability	f.s.d	failure probability	f.s.d	failure probability	f.s.d
case1_d1_mu0	2.916E-06	27.6%	2.070E-06	2.73%	2.158E-06	2.32%
case1_d2_mu0	9.254E-04	5.74%	8.183E-04	1.67%	7.863E-04	1.48%
case1_d3_mu0	1.183E-04	1.92%	1.212E-04	1.72%	1.208E-04	1.64%
case1_d4_mu0	7.624E-06	3.02%	7.757E-06	2.27%	8.211E-06	2.13%
case1_d5_mu0	4.217E-06	10.2%	4.959E-06	3.75%	5.063E-06	2.70%

Table 5.6 Results of the failure probability and f.s.d for the system repairability up

failure criteria	***LB method***		***ME method***		***Present work***	
	failure probability	f.s.d	failure probability	f.s.d	failure probability	f.s.d
case1_d1_fnrc	8.042E-08	12.1%	8.092E-08	12.1%	1.028E-07	11.0%
case1_d2_fnrc	6.191E-05	16.6%	4.571E-05	5.84%	4.468E-05	3.42%
case1_d3_fnrc	9.724E-06	10.6%	1.100E-05	9.12%	1.165E-05	9.41%
case1_d4_fnrc	3.323E-07	9.85%	3.505E-07	9.70%	3.918E-07	9.24%
case1_d5_fnrc	9.787E-08	10.1%	9.630E-08	7.85%	1.039E-07	7.75%

Table 5.7 Results of the failure probability and f.s.d for Case 5

failure criteria	LB method		ME method		Present work	
	failure probability	f.s.d	failure probability	f.s.d	failure probability	f.s.d
case5_d1	6.364E-09	8.29%	6.525E-09	7.96%	5.887E-09	7.37%
case5_d2	1.846E-05	45.0%	1.359E-05	22.5%	1.008E-05	9.27%
case5_d3	6.801E-07	6.95%	7.729E-07	7.19%	7.354E-07	6.74%
case5_d5	8.379E-09	24.0%	9.991E-09	11.3%	1.477E-08	7.45%

Table 5.8 Results of the failure probability and f.s.d for Case 6

failure criteria	LB method		ME method		Present work	
	failure probability	f.s.d	failure probability	f.s.d	failure probability	f.s.d
case6_d1	7.216E-10	24.1%	2.675E-09	62.1%	1.204E-09	11.1%
case6_d2	1.539E-05	45.7%	1.331E-05	15.2%	1.030E-05	13.3%
case6_d3	7.884E-10	34.6%	2.021E-09	60.8%	1.156E-09	15.8%
case6_d5	2.753E-09	71.9%	5.537E-09	22.8%	1.405E-08	17.4%

Table 5.9 Results of the CPU time and ratio of the effective history for Case 1

failure criteria	LB method			ME method			Present work		
	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number
case1_d1	85.3	4.4%	2.0E-2	194.6	13.6%	1.4E-2	118.7	56.7%	2.1E-3
case1_d2	14.1	20.7%	6.8E-4	25.2	53.4%	4.7E-4	17.9	83.6%	2.1E-4
case1_d3	71.4	11.4%	6.3E-3	142.3	23.1%	6.2E-3	88.0	57.9%	1.5E-3
case1_d4	61.6	11.7%	5.3E-3	125.3	19.7%	6.4E-3	78.6	47.9%	1.6E-3
case1_d5	80.3	6.9%	1.2E-2	174.0	16.5%	1.1E-2	109.3	61.6%	1.8E-3

Table 5.10 Results of the CPU time and ratio of the effective history for Case 2

failure criteria	LB method			ME method			Present work		
	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number
case2_d1	89.5	3.3%	2.7E-2	197.1	12.3%	1.6E-2	122.3	56.2%	2.1E-3
case2_d2	14.3	19.2%	7.4E-4	25.5	52.2%	4.9E-4	17.5	83.1%	2.0E-4
case2_d3	78.1	6.2%	1.3E-2	153.3	17.9%	8.6E-3	96.1	55.6%	1.7E-3
case2_d4	68.7	5.0%	1.4E-2	133.5	12.8%	1.0E-2	88.4	42.9%	2.0E-3
case2_d5	85.2	4.1%	2.1E-2	181.4	13.8%	1.3E-2	112.5	60.2%	1.9E-3

Table 5.11 Results of the CPU time and ratio of the effective history for Case 3

failure criteria	***LB method***			***ME method***			***Present work***		
	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number
case3_d1	87.6	1.7%	5.2E-2	193.5	11.3%	1.7E-2	119.3	55.4%	2.1E-3
case3_d2	15.2	14.5%	1.1E-3	26.3	50.3%	5.2E-4	17.6	82.3%	2.1E-4
case3_d3	77.6	2.3%	3.4E-2	151.2	15.2%	9.9E-3	93.4	53.4%	1.7E-3
case3_d4	66.3	1.6%	4.1E-2	129.9	10.0%	1.3E-2	83.1	39.5%	2.1E-3
case3_d5	83.5	1.9%	4.4E-2	179.9	12.3%	1.5E-2	109.1	59.0%	1.8E-3

Table 5.12 Results of the CPU time and ratio of the effective history for Case 4

failure criteria	***LB method***			***ME method***			***Present work***		
	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number
case4_d1	140.6	2.1%	6.8E-2	291.4	11.5%	2.5E-2	195.6	56.7%	3.4E-3
case4_d2	30.5	8.4%	3.6E-3	51.2	49.4%	1.0E-3	36.1	80.1%	4.4E-4
case4_d3	137.8	4.3%	3.2E-2	276.2	14.6%	1.9E-2	191.9	53.2%	3.5E-3
case4_d4	128.5	4.0%	3.2E-2	264.3	10.6%	2.5E-2	191.7	42.1%	4.4E-3
case4_d5	136.5	7.5%	1.8E-2	269.4	27.5%	9.8E-3	175.4	74.0%	2.4E-3

Table 5.13 Results of the CPU time and ratio of the effective history for unrepaired system

failure criteria	LB method			ME method			Present work		
	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number
case1_d1_mu0	77.2	4.4%	1.8E-2	192.2	12.6%	1.5E-2	114.4	64.6%	1.7E-3
case1_d2_mu0	13.2	25.9%	5.1E-4	24.0	61.1%	3.9E-4	14.6	89.8%	1.6E-4
case1_d3_mu0	71.4	11.0%	6.5E-3	174.8	20.3%	8.6E-3	107.3	66.6%	1.6E-3
case1_d4_mu0	69.3	12.3%	5.6E-3	167.1	21.9%	7.6E-3	107.5	65.7%	1.6E-3
case1_d5_mu0	72.5	7.8%	9.3E-3	170.4	20.7%	8.2E-3	95.2	75.2%	1.2E-3

Table 5.14 Results of the CPU time and ratio of the effective history for the system repairability up

failure criteria	LB method			ME method			Present work		
	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number
case1_d1_fnrc	76.4	2.5%	3.0E-2	176.3	5.0%	3.5E-2	113.4	20.9%	5.3E-3
case1_d2_fnrc	13.3	15.1%	8.8E-4	25.7	34.0%	7.6E-4	17.5	58.4%	2.8E-4
case1_d3_fnrc	67.2	7.7%	8.7E-3	136.1	12.1%	1.1E-2	86.2	23.8%	3.5E-3
case1_d4_fnrc	57.2	6.9%	8.3E-3	116.5	9.3%	1.3E-2	79.4	18.1%	4.3E-3
case1_d5_fnrc	72.4	4.2%	1.7E-2	161.2	6.8%	2.4E-2	104.0	17.7%	5.7E-3

Table 5.15 Results of the CPU time and ratio of the effective history for Case 5

failure criteria	***LB method***			***ME method***			***Present work***		
	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number
case5_d1	155.2	1.4%	1.1E-1	344.6	5.0%	6.9E-2	250.1	42.3%	5.9E-3
case5_d2	29.3	11.3%	2.6E-3	51.3	40.5%	1.3E-3	39.6	74.8%	5.3E-4
case5_d3	175.3	4.4%	4.0E-2	393.2	9.5%	4.1E-2	313.1	36.4%	8.6E-3
case5_d5	149.2	2.6%	5.7E-2	332.3	7.5%	4.4E-2	234.4	47.4%	4.9E-3

Table 5.16 Results of the CPU time and ratio of the effective history for Case 6

failure criteria	***LB method***			***ME method***			***Present work***		
	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number	CPU time (min.)	ratio of the effective history	CPU time / effective history number
case6_d1	172.2	0.7%	2.5E-1	366.5	4.0%	9.2E-2	268.6	42.0%	6.4E-3
case6_d2	34.2	10.0%	3.4E-3	57.1	39.3%	1.5E-3	45.3	74.3%	6.1E-4
case6_d3	197.2	1.2%	1.6E-1	426.3	5.7%	7.5E-2	346.2	33.6%	1.0E-2
case6_d5	167.2	1.0%	1.7E-1	346.5	5.8%	5.9E-2	256.2	46.1%	5.6E-3

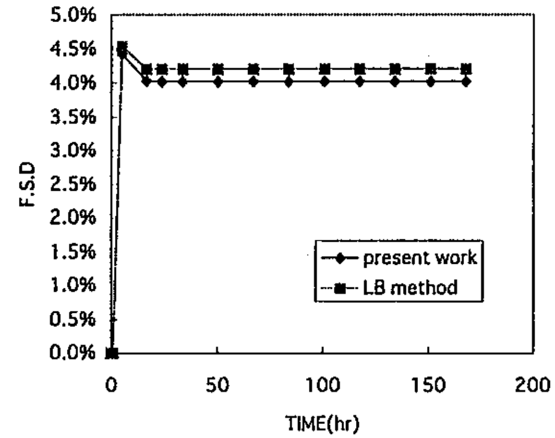

Fig.5.1 Comparison of f.s.d results for case1_d1

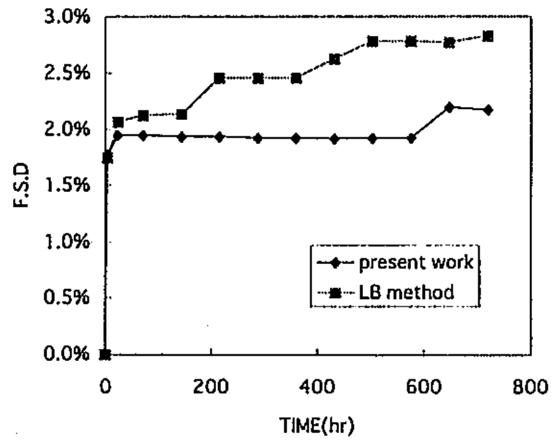

Fig.5.2 Comparison of f.s.d results for case1_d2

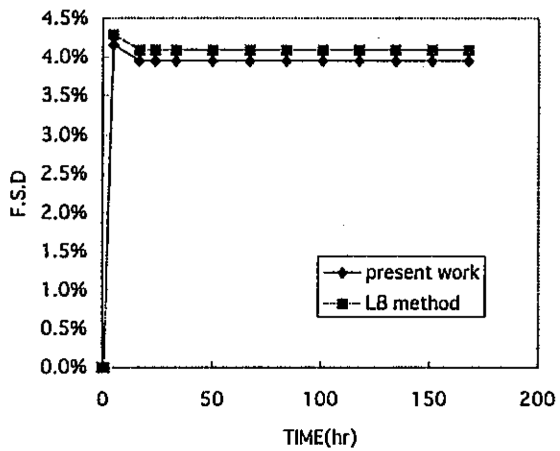

Fig.5.3 Comparison of f.s.d results for case1_d3

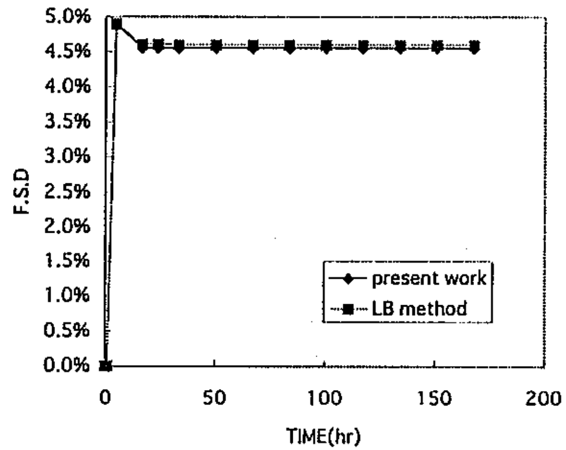

Fig.5.4 Comparison of f.s.d results for case1_d4

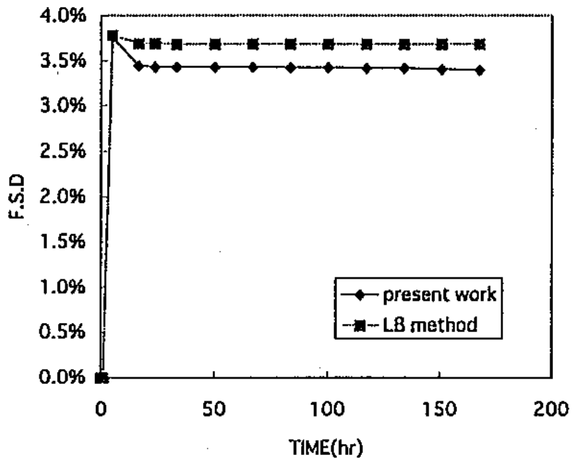

Fig.5.5 Comparison of f.s.d results for case1_d5

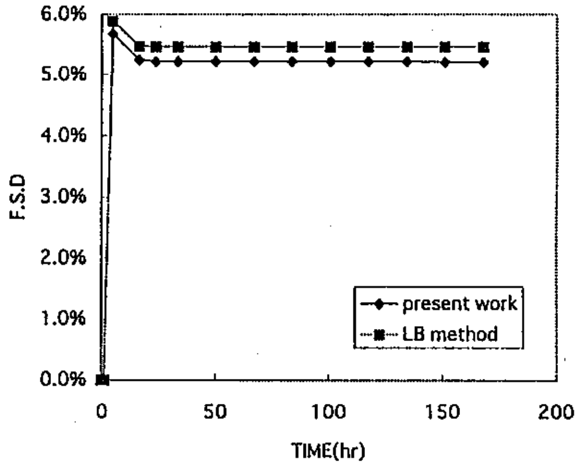

Fig.5.6 Comparison of f.s.d results for case2_d1

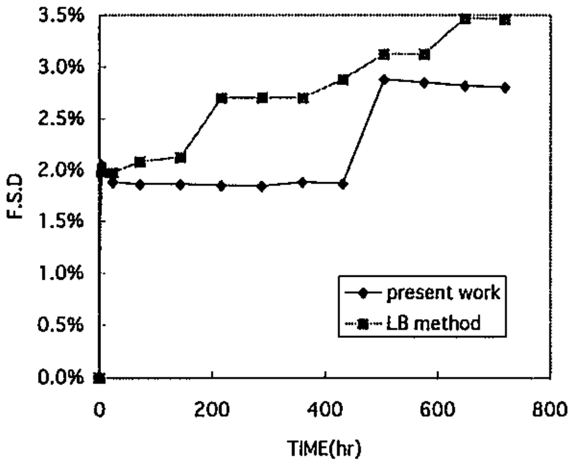

Fig.5.7 Comparison of f.s.d results for case2_d2

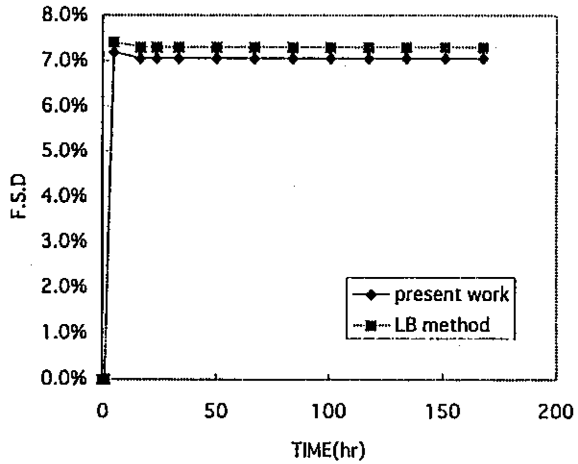

Fig.5.8 Comparison of f.s.d results for case2_d3

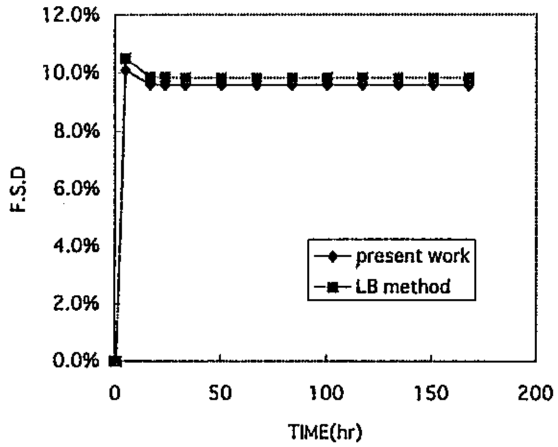

Fig.5.9 Comparison of f.s.d results for case 2 _d4

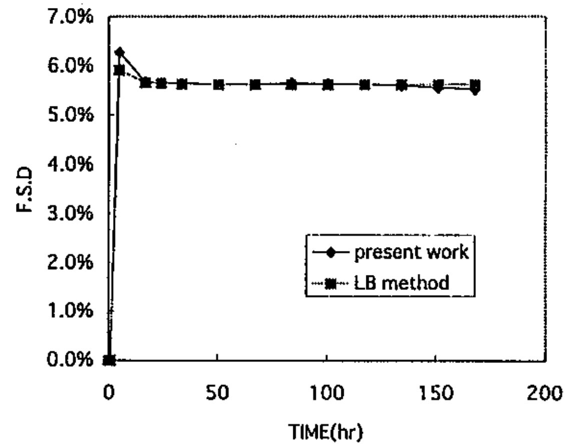

Fig.5.10 Comparison of f.s.d results for case2_d5

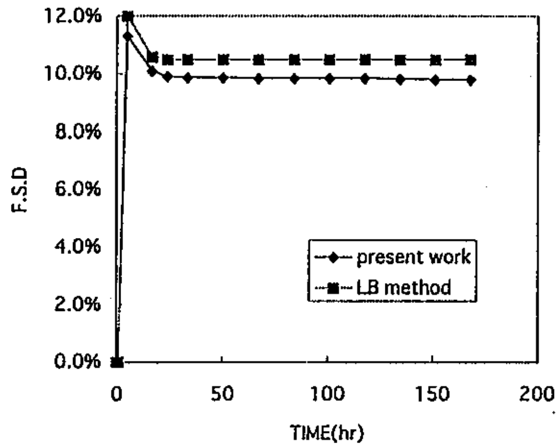

Fig.5.11 Comparison of f.s.d results for case3_d1

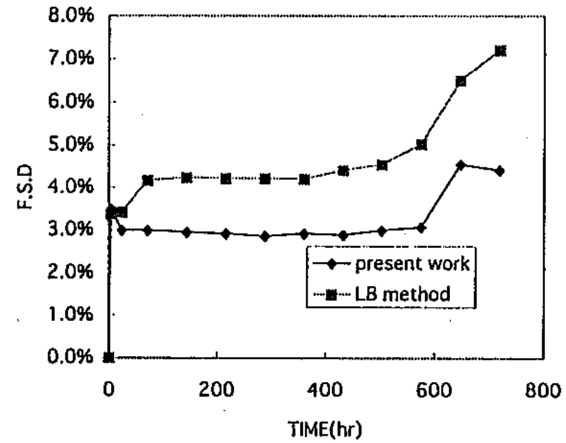

Fig.5.12 Comparison of f.s.d results for case3_d2

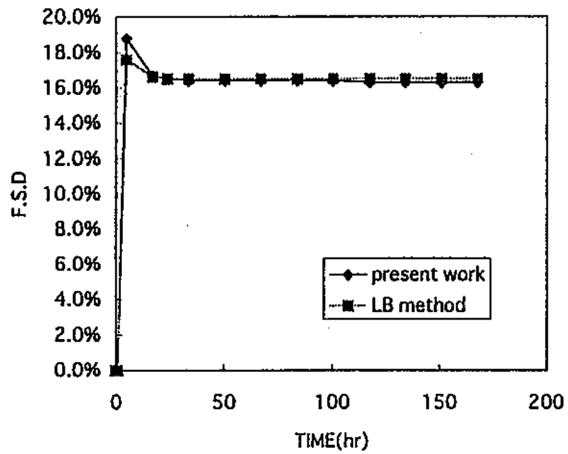

Fig.5.13 Comparison of f.s.d results for case3_d3

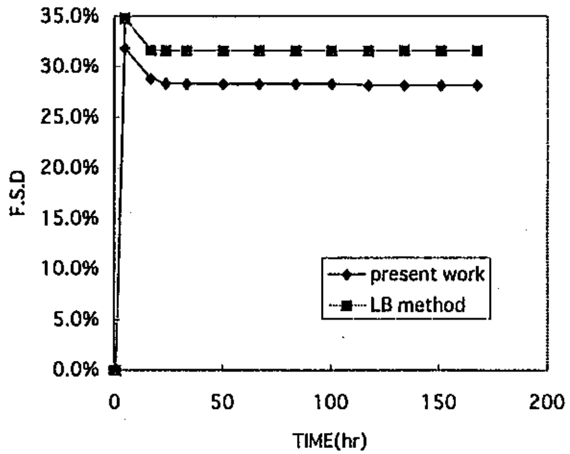

Fig.5.14 Comparison of f.s.d results for case3_d4

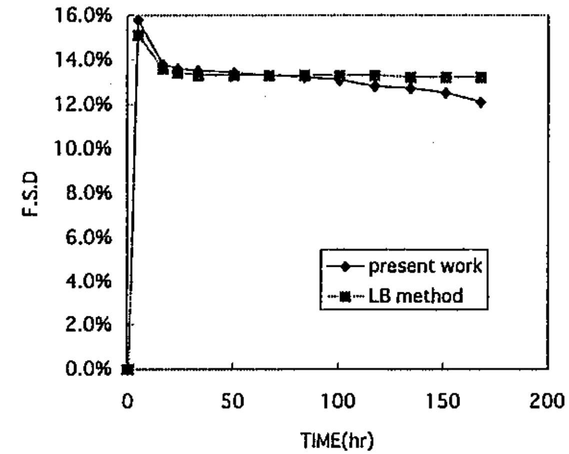

Fig.5.15 Comparison of f.s.d results for case3_d5

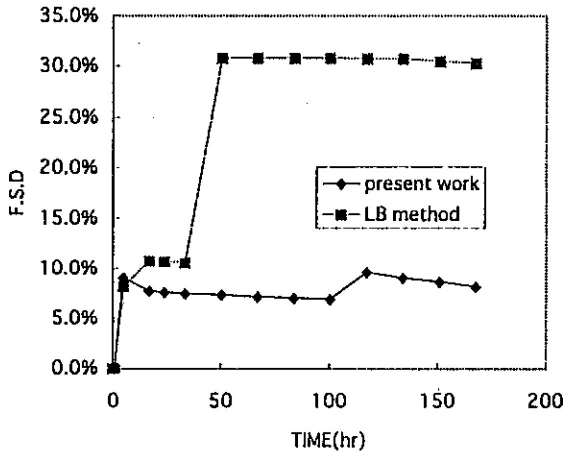

Fig.5.16 Comparison of f.s.d results for case4_d1

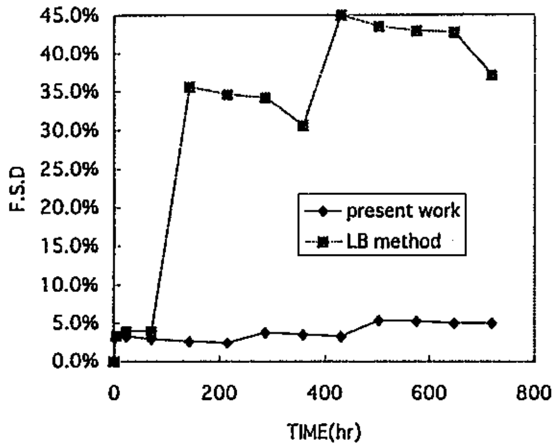

Fig.5.17 Comparison of f.s.d results for case4_d2

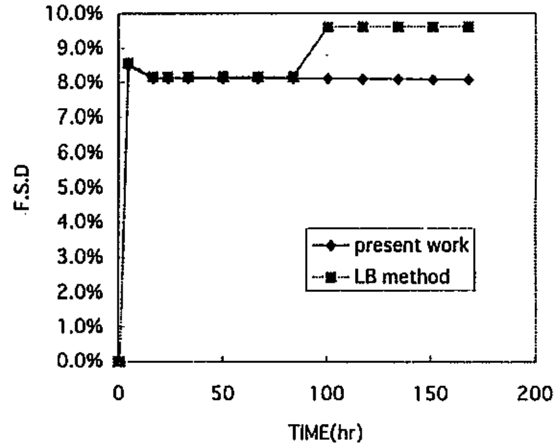

Fig.5.18 Comparison of f.s.d results for case4_d3

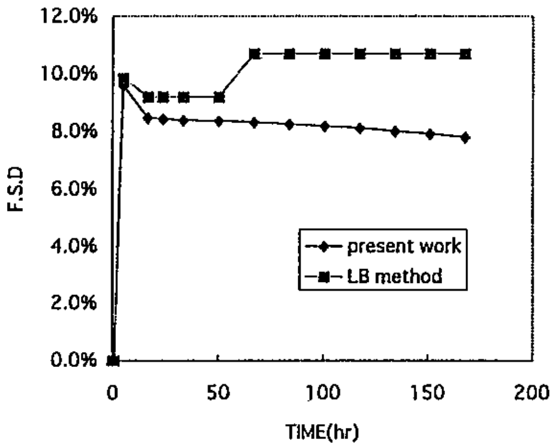

Fig.5.19 Comparison of f.s.d results for case4_d4

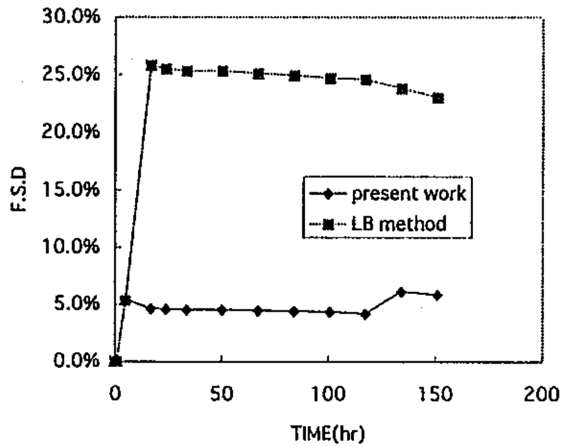

Fig.5.20 Comparison of f.s.d results for case4_d5

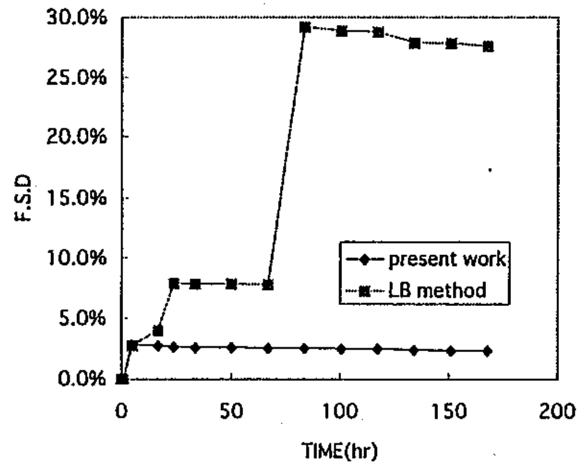

Fig.5.21 Comparison of f.s.d results for case1_d1_mu0

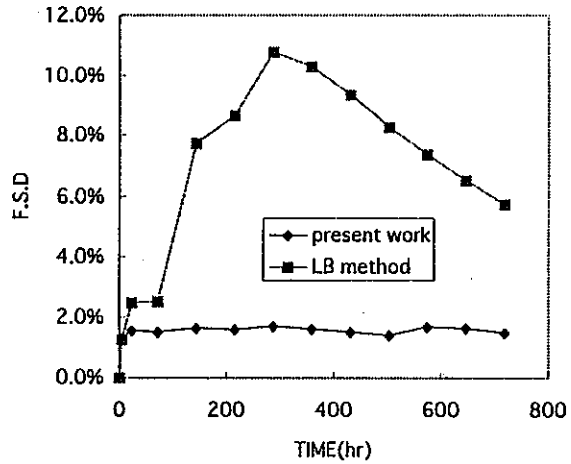

Fig.5.22 Comparison of f.s.d results for case1_d2_mu0

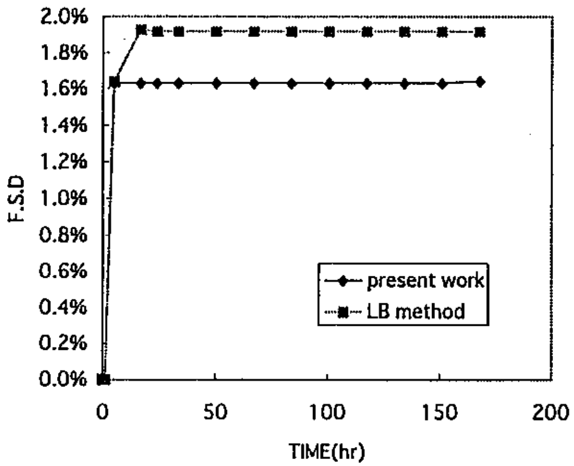

Fig.5.23 Comparison of f.s.d results for case1_d3_mu0

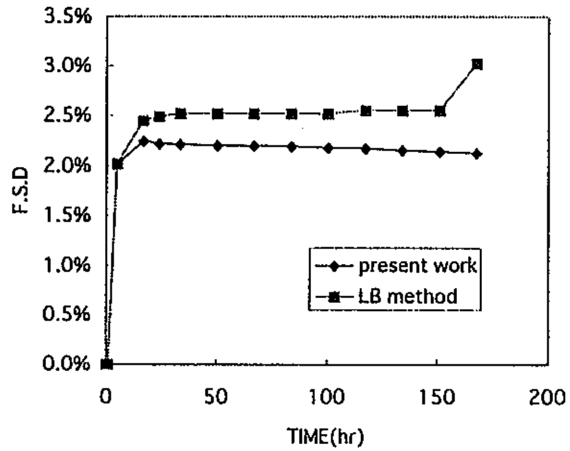

Fig.5.24 Comparison of f.s.d results for case1_d4_mu0

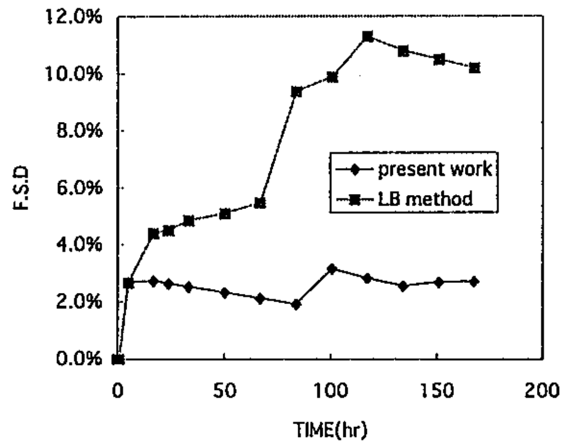

Fig.5.25 Comparison of f.s.d results for case1_d5_mu0

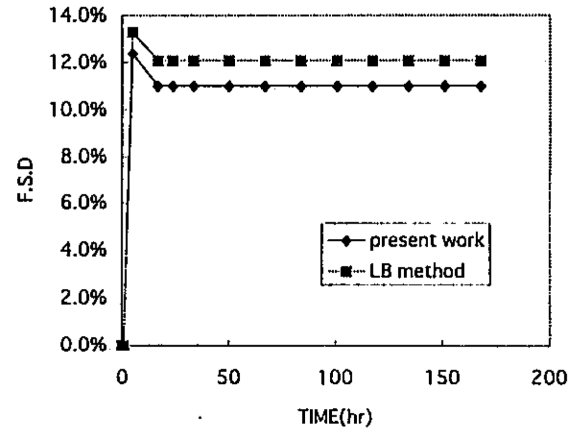

Fig.5.26 Comparison of f.s.d results for case1_d1_fnrc

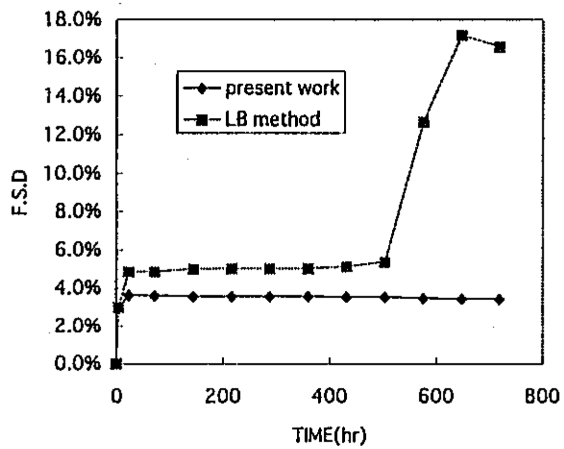

Fig.5.27 Comparison of f.s.d results for case1_d2_fnrc

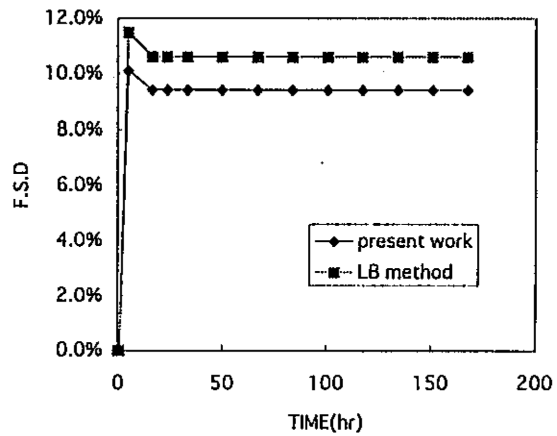

Fig.5.28 Comparison of f.s.d results for case1_d3_fnrc

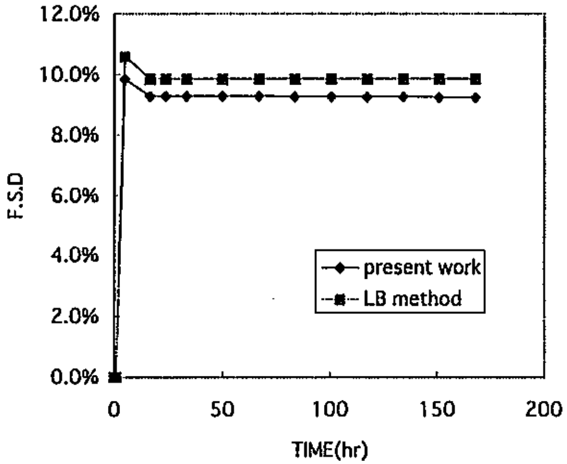

Fig.5.29 Comparison of f.s.d results for case1_d4_fnrc

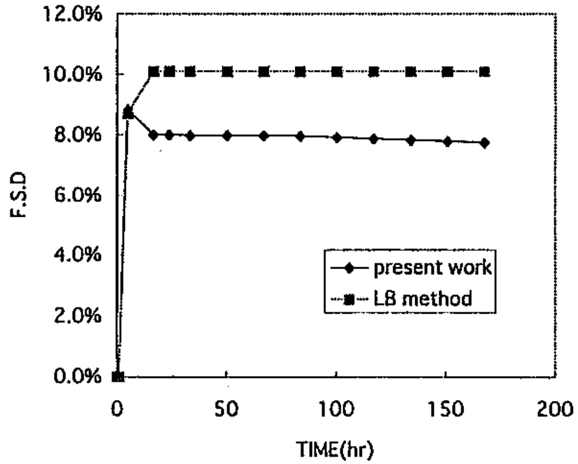

Fig.5.30 Comparison of f.s.d results for case1_d5_fnrc

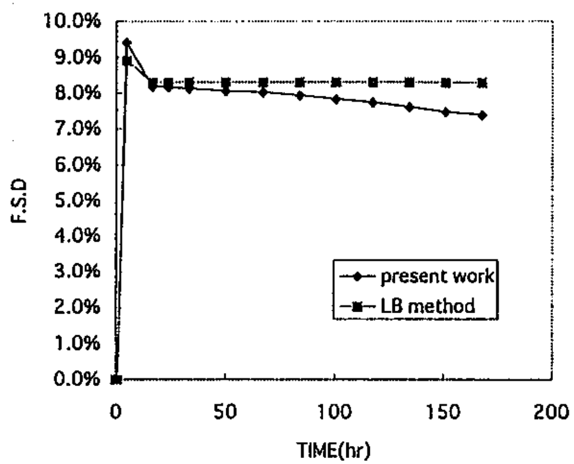

Fig.5.31 Comparison of f.s.d results for case5_d1

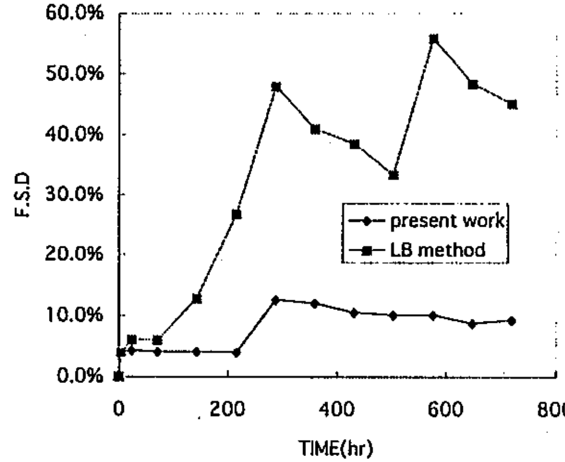

Fig.5.32 Comparison of f.s.d results for case5_d2

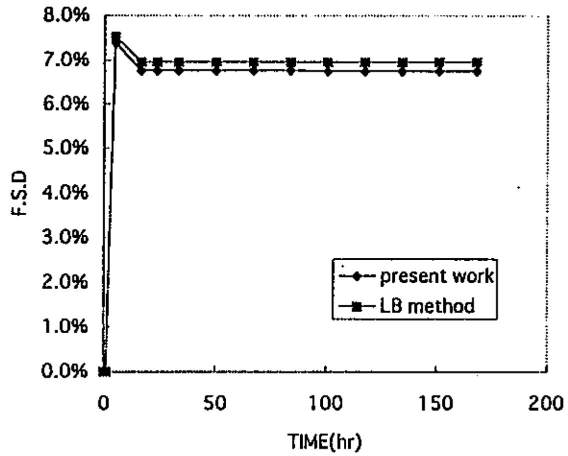

Fig.5.33 Comparison of f.s.d results for case5_d3

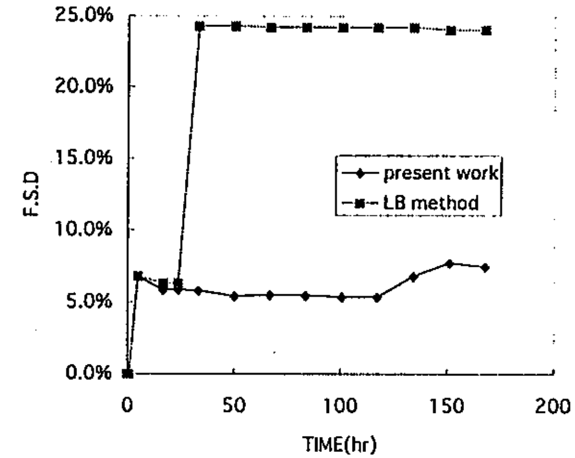

Fig.5.34 Comparison of f.s.d results for case5_d5

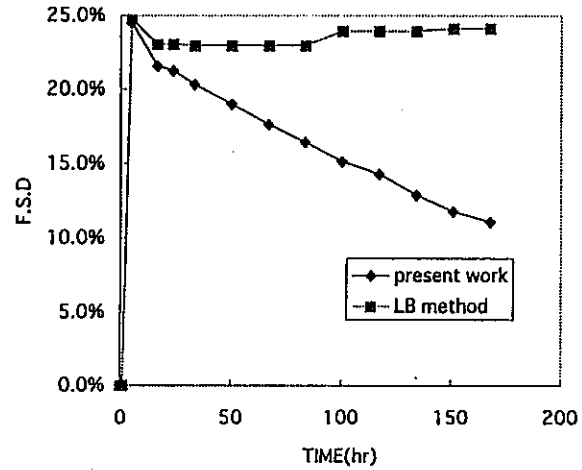

Fig.5.35 Comparison of f.s.d results for case6_d1

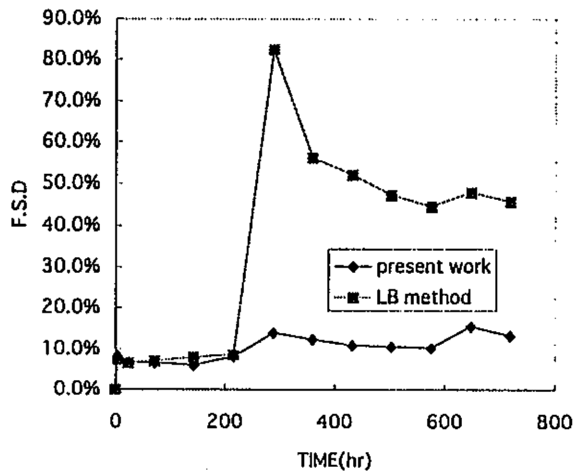

Fig.5.36 Comparison of f.s.d results for case6_d2

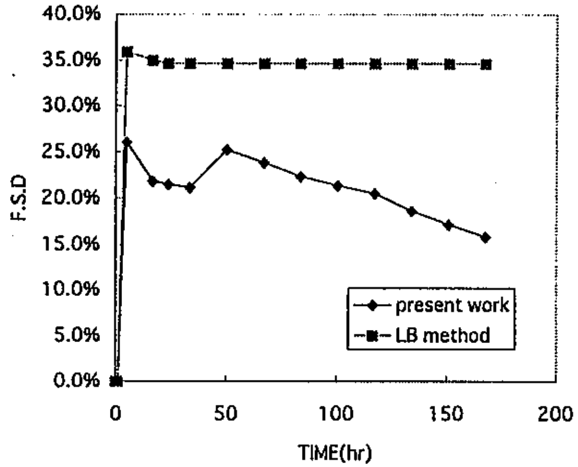

Fig.5.37 Comparison of f.s.d results for case6_d3

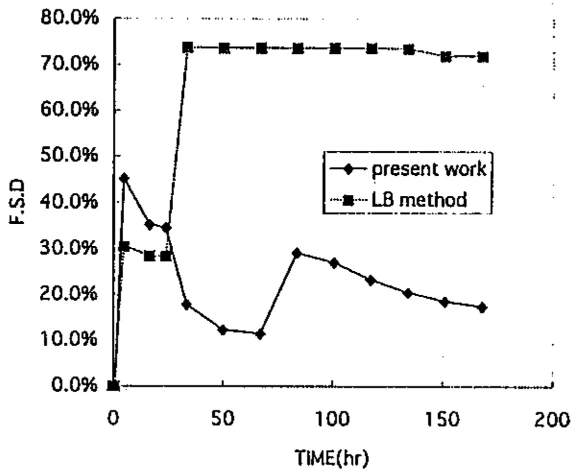

Fig.5.38 Comparison of f.s.d results for case6_d5

From Table 5.1, 5.2 and Figure 5.1 - 5.10, we know that the errors (f.s.d) obtained from LB method are consistent with those obtained from present method, which indicate that both methods can be adopted in Case 1 and Case 2.

Moreover, from Table 5.4, 5.5, 5.6, 5.7,5.8 and Figure 5.16 - 5.38, we can clearly see that further reduction in the errors (f.s.d) is the prominent outcome of the present work. This is because sufficient effective history numbers are obtained by using present method, therefore, reasonable statistics of results can be attained. It should be noted that in these cases the improvement of the effective history number is mainly due to the fact that in the LB method the component can be only sampled depending on the natural failure probability, therefore when biasing is applied there is no distinction between the cut sets. However, with the method of biasing of the transitions towards the closest cut set by introducing the concept of the distance between the present state and cut sets, we can bias the transitions towards the cut set which is more likely to fail. In this way, the number of failed histories is increased, as we anticipated.

However, Table 5.3 shows that both methods are not very effective for the case3_d3, case3_d4 and case3_d5. But if we analyze the results in more detail, we see that a potential major contributor to the failure probability of each case is its unavailability, and from Figure 5.13, 5.14, 5.15 , we can clearly see that the total error is governed by the error due to demand failure sampling. Similarly for case1_d1_fnrc, a case in which we considered the improvement of the repairability of the component FNRC. we can solve the problem by increasing the demand biasing parameter of the component FNRC from 0.2 to 0.5. In this way, sufficient effective history numbers can be obtained during demand sampling, therefore statistical significant results can be gained. For case3_d3, case3_d4, case3_d5 and case1_d1_fnrc which errors (f.s.d) are greater than 10 percent, we recalculated the errors with the increased demand biasing parameter of 0.5 for the component FNRC and the results are given in Table 5.17. Indeed, the results show its effectiveness.

Table 5.17 Comparison of Monte Carlo failure probability and f.s.d results for the case in which the error is governed by demand failure sampling

failure criteria	*Demand biasing value of FNRC (0.2)*		*Demand biasing value of FNRC (0.5)*	
	failure probability	f.s.d	failure probability	f.s.d
case3_d3	9.792E-08	16.3%	8.903E-08	6.00%
case3_d4	1.050E-07	28.2%	9.670E-08	7.95%
case3_d5	9.757E-08	12.1%	1.024E-07	6.14%
case1_d1_fnrc	1.028E-07	11.0%	8.045E-08	8.47%

Returning to the Case 6 study, when we assume that 100% heat removal capacity of IRACS-NC can be attained by 1 loop, and we consider the heat removal capacity of the WSS in the first 24 hours, the occurrence of decay heat removal system failure is really a rare event for the case D1, D3 and D5. Table 5.8 shows that the errors obtained from LB method and ME method are so large that the results have little meaning. Compared with these two methods, the errors calculated by present work are relatively small but still larger then 10 percent. If we further analyze the results, we can see that unreliability plays an important role in the failure probability calculation, especially for the case D2 and D5. It should be noted that when we alter the natural probabilities aiming at favouring events, the alternative, unfavoured events may still occur, even with less frequency. When this latter contributes to the estimation of unreliability, its larger weights may deteriorate the resulting statistics, unless a very larger number of trials is performed. In order to address this problem, based on our experience and observations, we changed the demand biasing parameter of the component FNRC and component WSSS, and adjusted the biasing value X used in the unreliability calculation. The parameters are given in Table 5.18, and the results are shown in Table 5.19.

Table 5.18 The change of biasing value in the Case 6

failure criteria	***Demand biasing value of FNRC***	***Demand biasing value of WSSS***	***biasing value X used in the unreliability calculation***
case6_d1	0.5	0.2	0.95
case6_d2	0.5	0.05	0.5
case6_d3	0.5	0.5	0.9
case6_d5	0.4	0.3	0.95

Table 5.19 Comparison of Monte Carlo failure probability and f.s.d results for the case in which the error is governed by unreliability calculation

failure criteria	***Results before biasing value changed***		***Results after biasing value changed***	
	failure probability	f.s.d	failure probability	f.s.d
case6_d1	1.20E-09	11.10%	1.21E-09	9.39%
case6_d2	1.03E-05	13.30%	9.57E-06	9.80%
case6_d3	1.16E-09	15.80%	8.98E-10	6.78%
case6_d5	1.41E-08	17.40%	8.504E-09	10.3%

Table 5.19 show that when the total error is governed by unreliability calculations, it is very difficult to further decrease it, especially for cases D2 and D5. Also it should be mentioned that the biasing value setting is case dependent.

It is difficult to find out a perfect technique to assign the biasing values for the demand failure sampling. Based on our experience and observations, we assigned the biasing values according to the importance measure of each component and its repairability, i.e. the higher importance of the component and the more probable can be repaired, then the larger biasing value it is.

Meanwhile, The plots of the f.s.d vs. the total number of histories are shown in Figure 5.39 - 5.76. As seen in Fig.5.77, if we assume the reasonable statistical results can be obtained from the errors less than 20 percent, 40 thousand of histories are enough to get the practicable answer for most cases. But if we want to get less errors, e.g. the errors are less than 10 percent, we had better to simulate 100 thousand of histories.

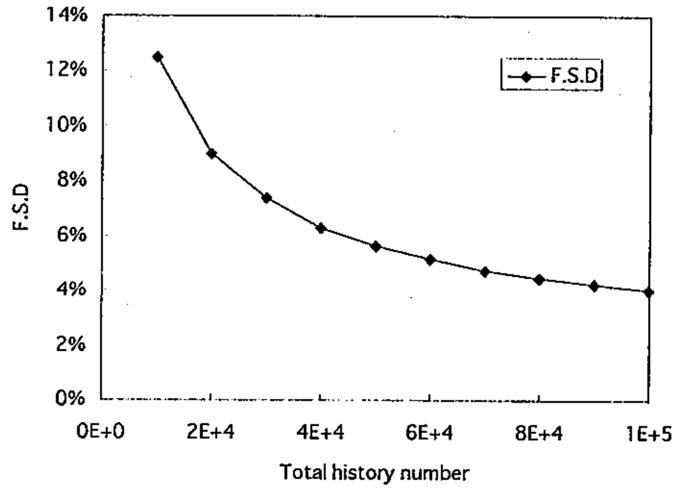

Fig.5.39 F.S.D vs. total history number for Case1_d1

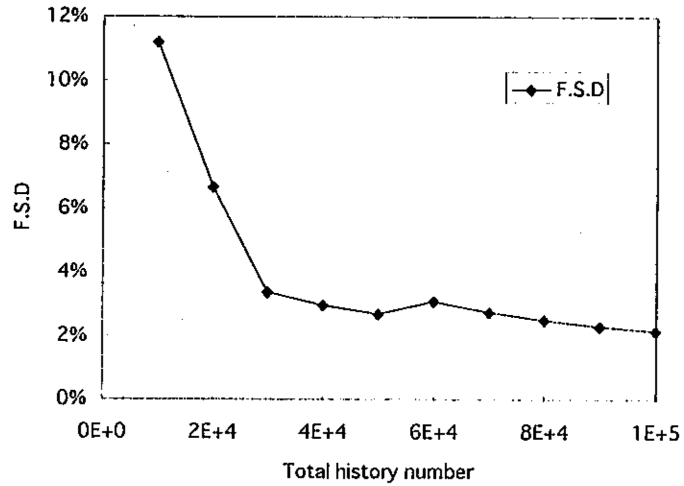

Fig.5.40 F.S.D vs. total history number for Case1_d2

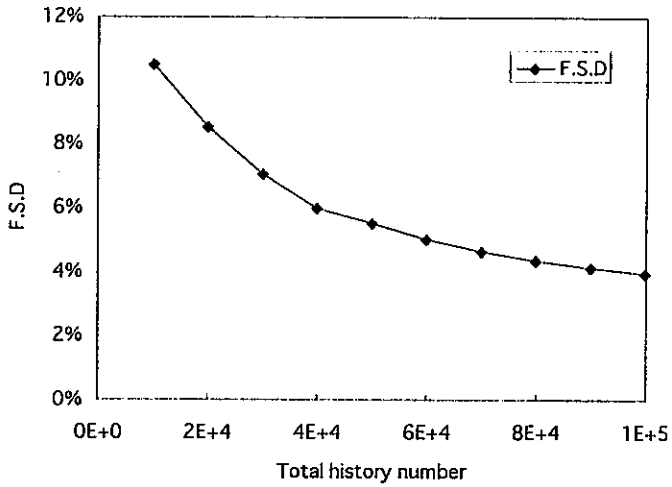

Fig.5.41 F.S.D vs. total history number for Case1_d3

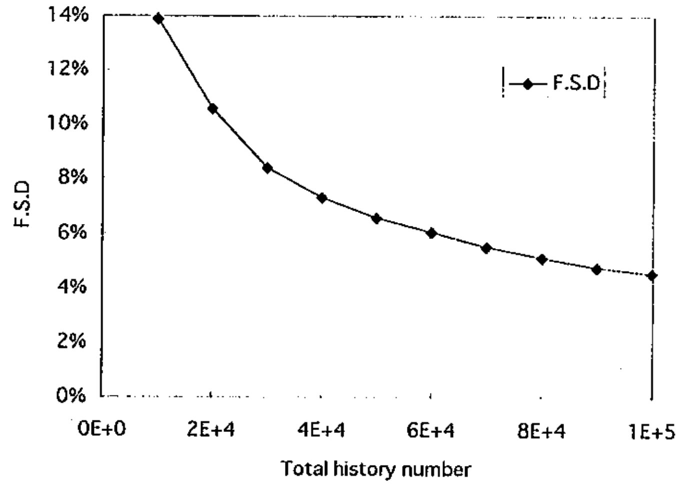

Fig.5.42 F.S.D vs. total history number for Case1_d4

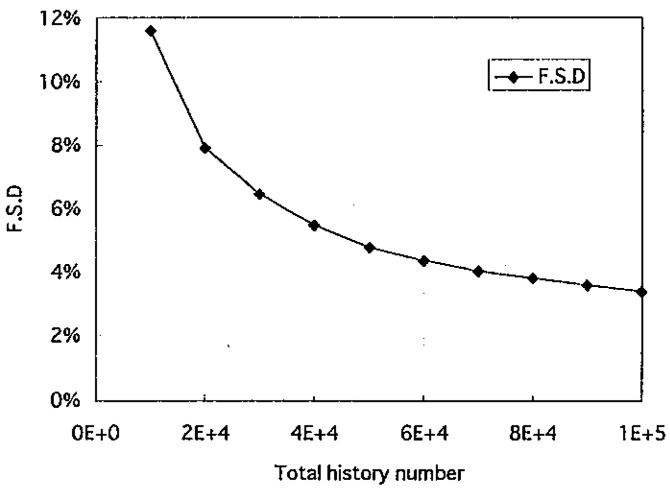

Fig.5.43 F.S.D vs. total history number for Case1_d5

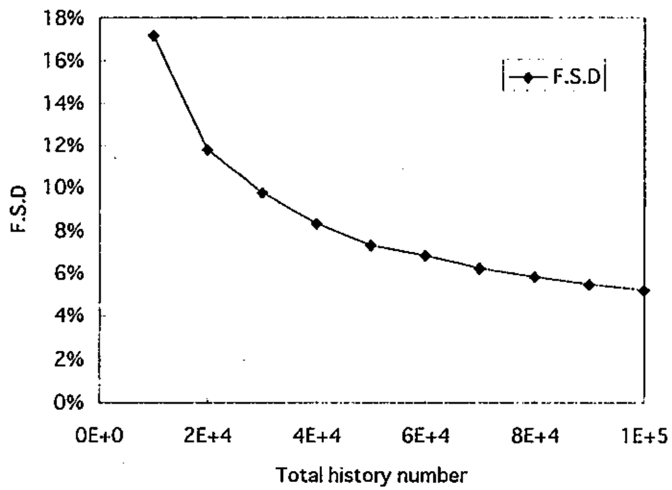

Fig.5.44 F.S.D vs. total history number for Case2_d1

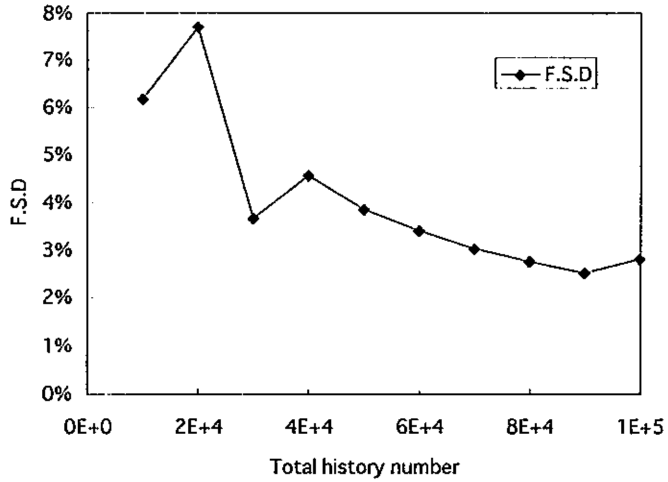

Fig.5.45 F.S.D vs. total history number for Case2_d2

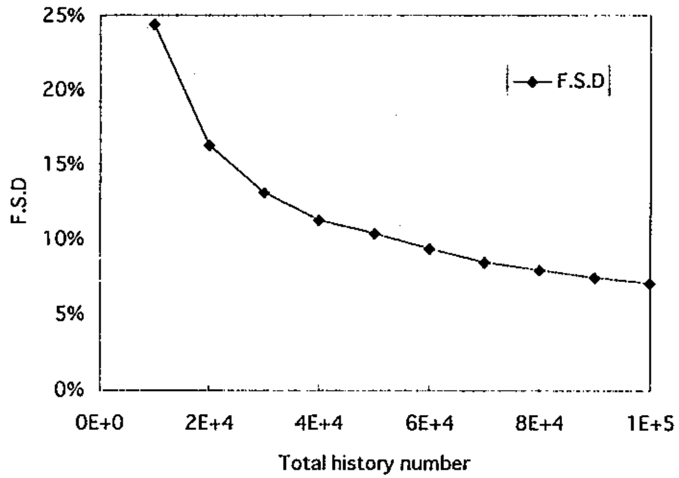

Fig.5.46 F.S.D vs. total history number for Case2_d3

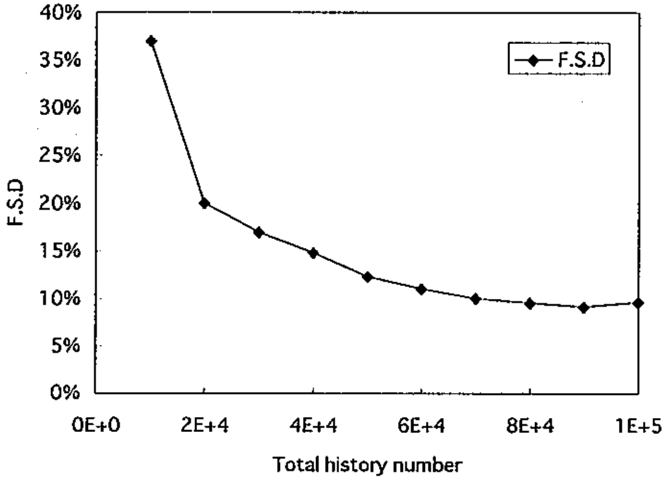

Fig.5.47 F.S.D vs. total history number for Case2_d4

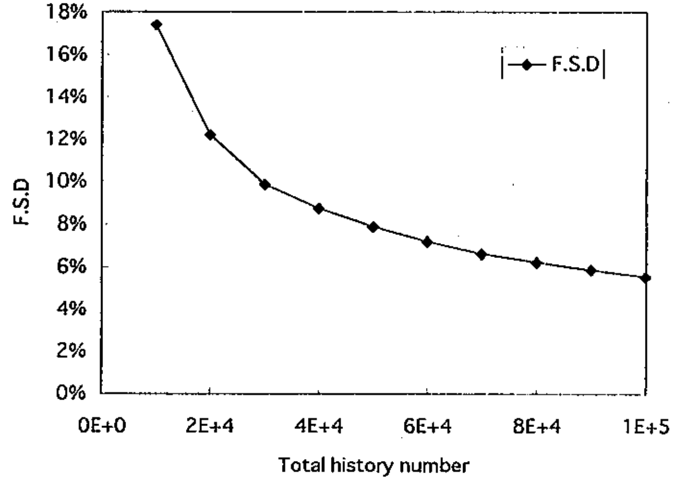

Fig.5.48 F.S.D vs. total history number for Case2_d5

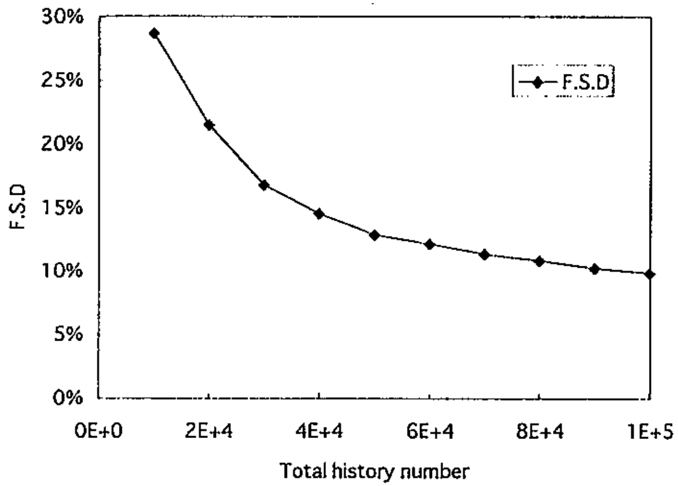

Fig.5.49 F.S.D vs. total history number for Case3_d1

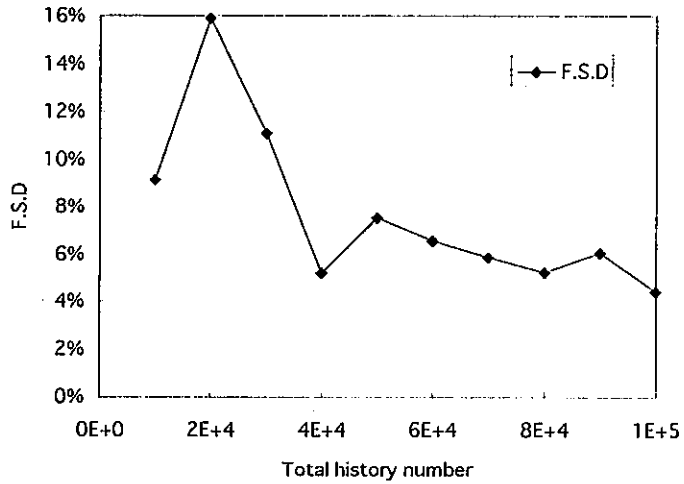

Fig.5.50 F.S.D vs. total history number for Case3_d2

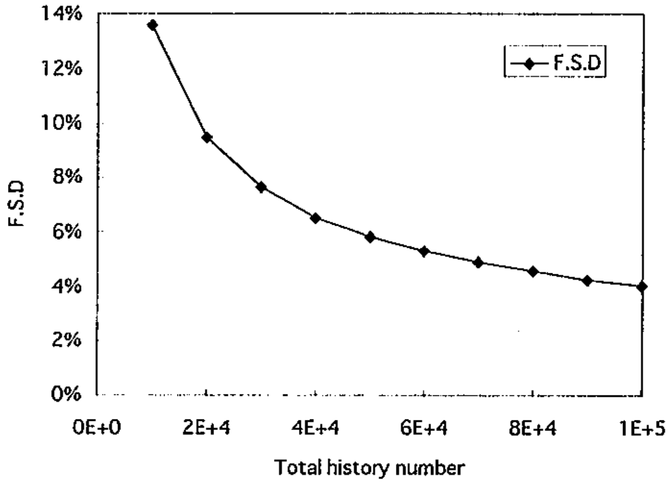

Fig.5.51 F.S.D vs. total history number for Case3_d3 (FNRC: 0.5)

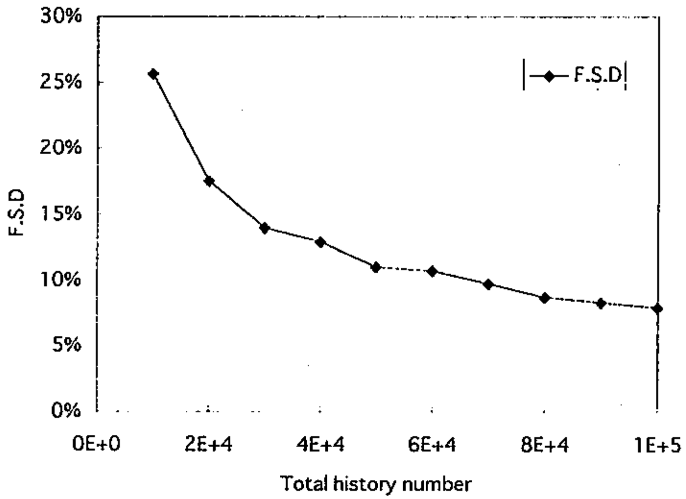

Fig.5.52 F.S.D vs. total history number for Case3_d4 (FNRC: 0.5)

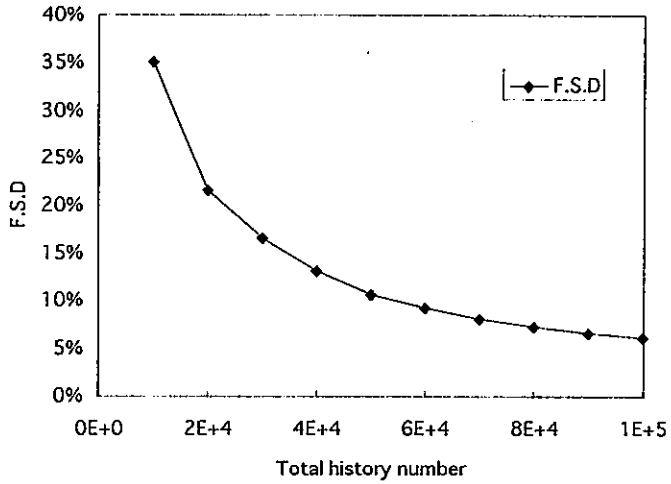

Fig.5.53 F.S.D vs. total history number for Case3_d5 (FNRC: 0.5)

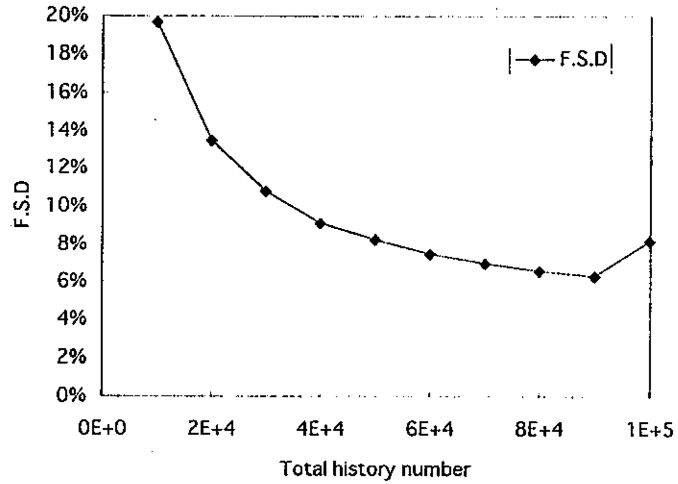

Fig.5.54 F.S.D vs. total history number for Case4_d1

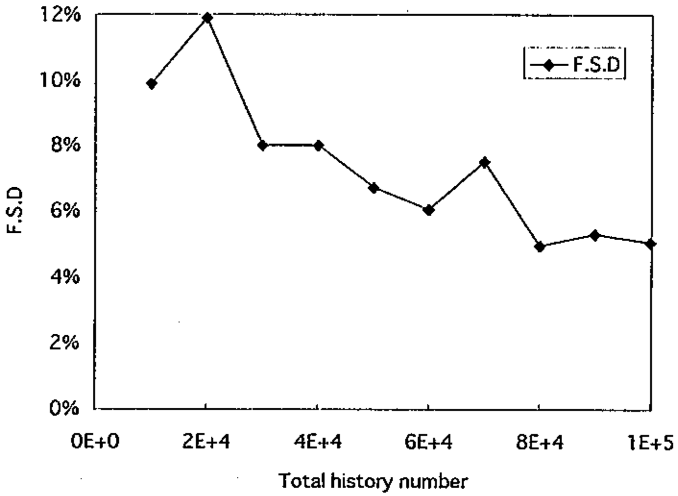

Fig.5.55 F.S.D vs. total history number for Case4_d2

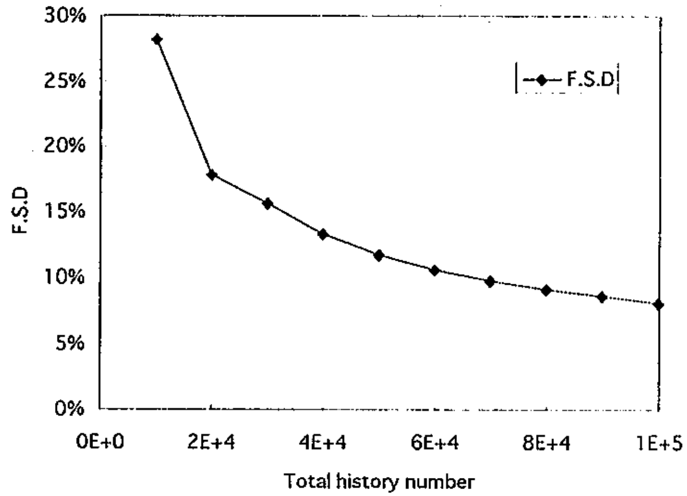

Fig.5.56 F.S.D vs. total history number for Case4_d3

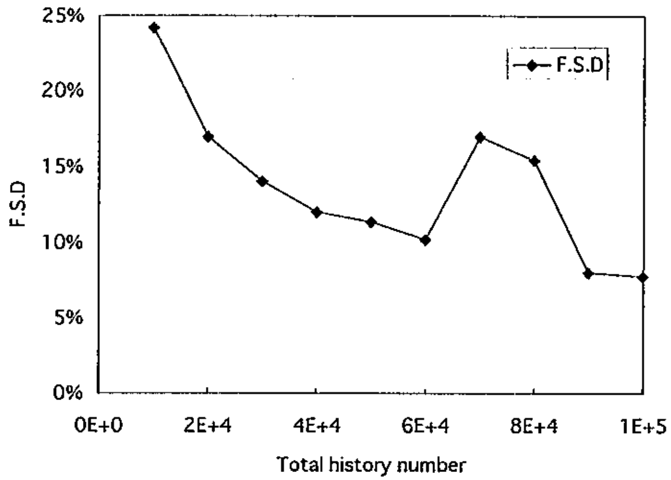

Fig.5.57 F.S.D vs. total history number for Case4_d4

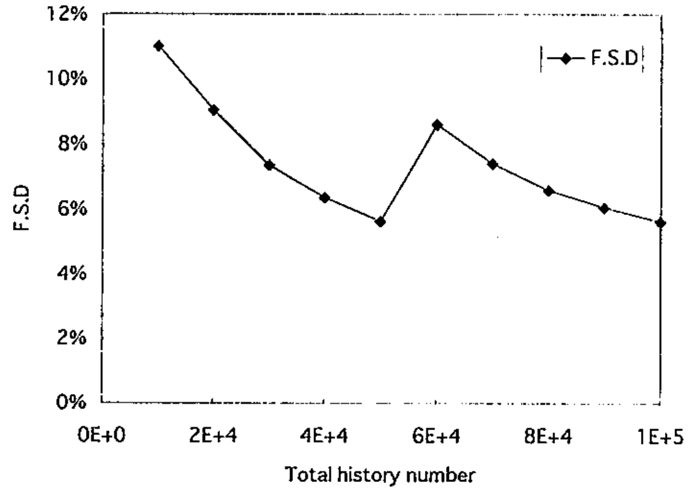

Fig.5.58 F.S.D vs. total history number for Case4_d5

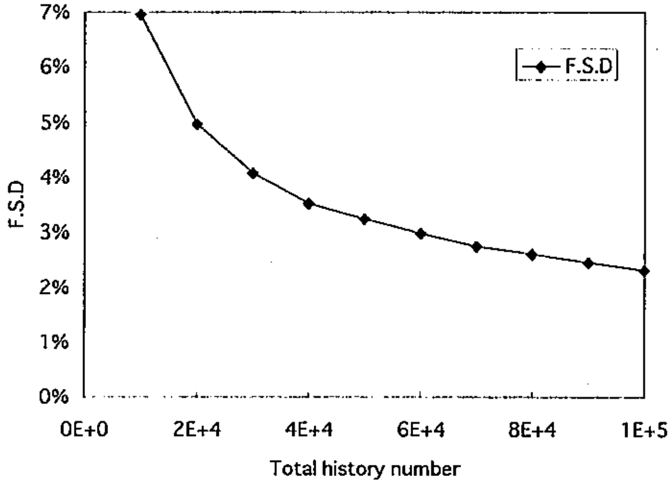

Fig.5.59 F.S.D vs. total history number for Case1_d1_mu0

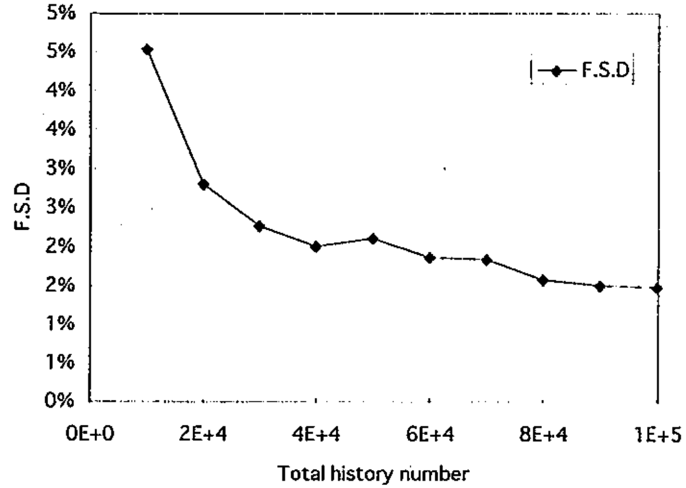

Fig.5.60 F.S.D vs. total history number for Case1_d2_mu0

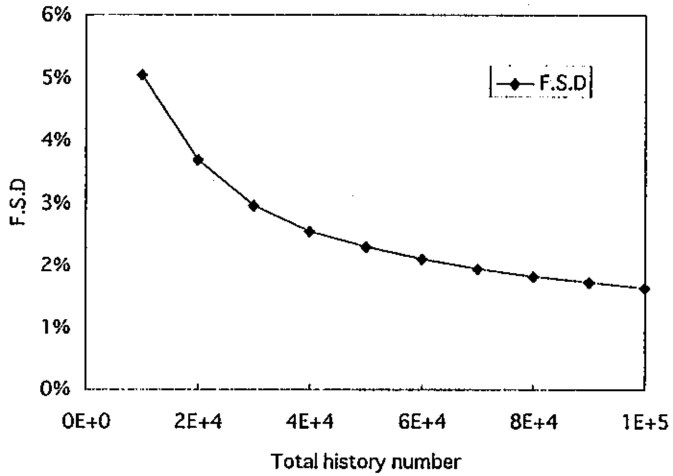

Fig.5.61 F.S.D vs. total history number for Case1_d3_mu0

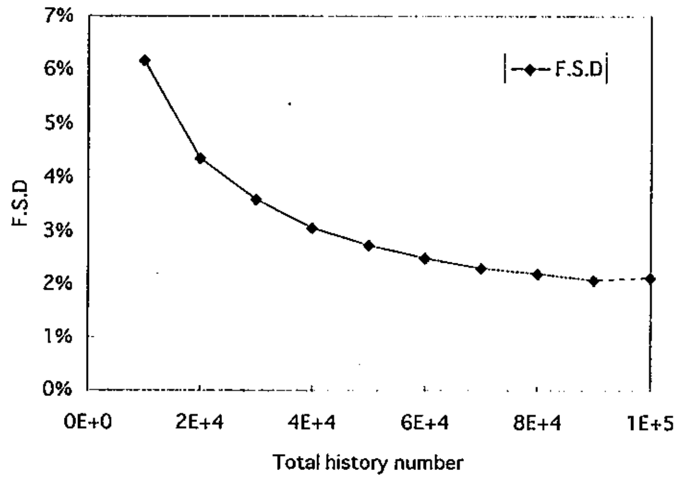

Fig.5.62 F.S.D vs. total history number for Case1_d4_mu0

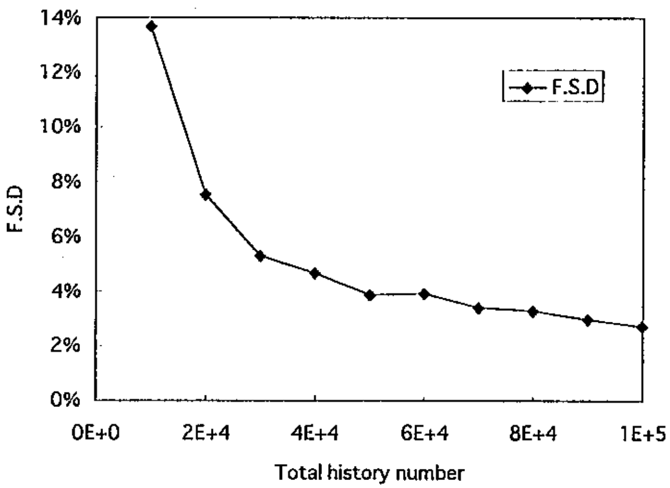

Fig.5.63 F.S.D vs. total history number for Case1_d5_mu0

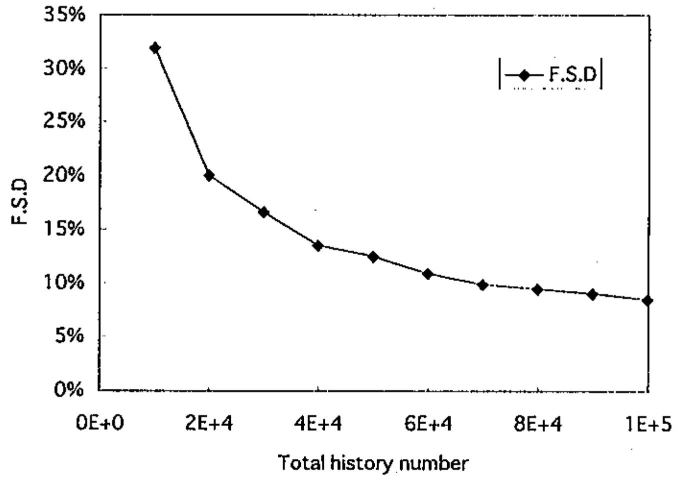

Fig.5.64 F.S.D vs. total history number forCase1_d1_fnrc
(FNRC: 0.5)

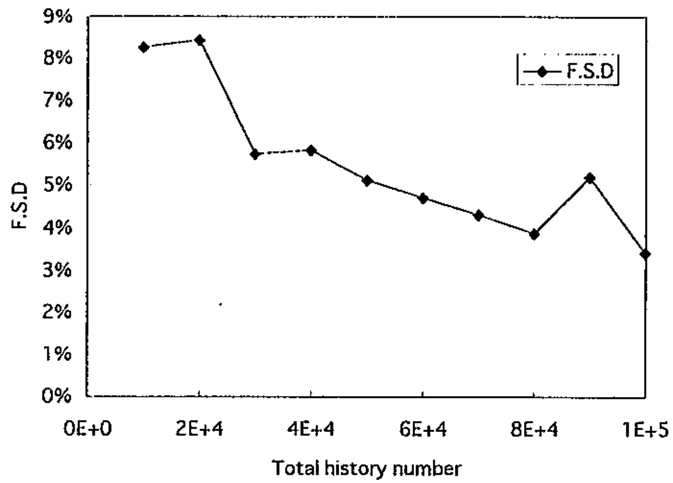

Fig.5.65 F.S.D vs. total history number for Case1_d2_fnrc

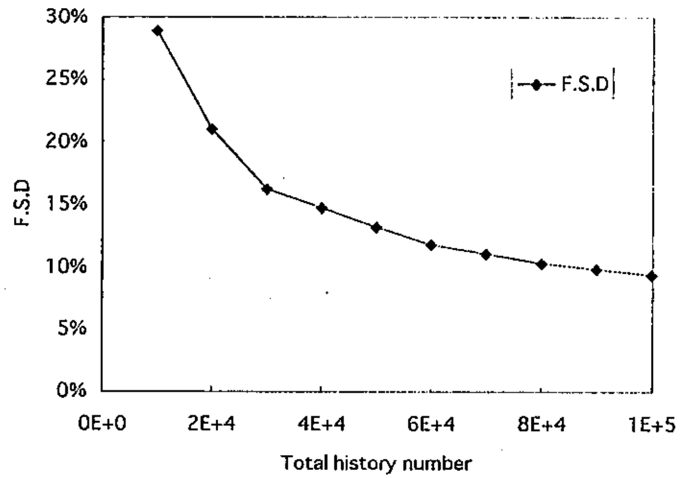

Fig.5.66 F.S.D vs. total history number for Case1_d3_fnrc

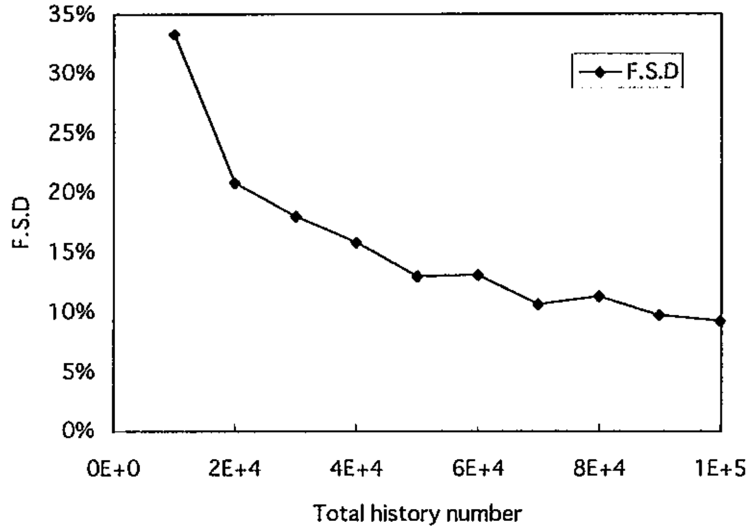

Fig.5.67 F.S.D vs. total history number for Case1_d4_fnrc

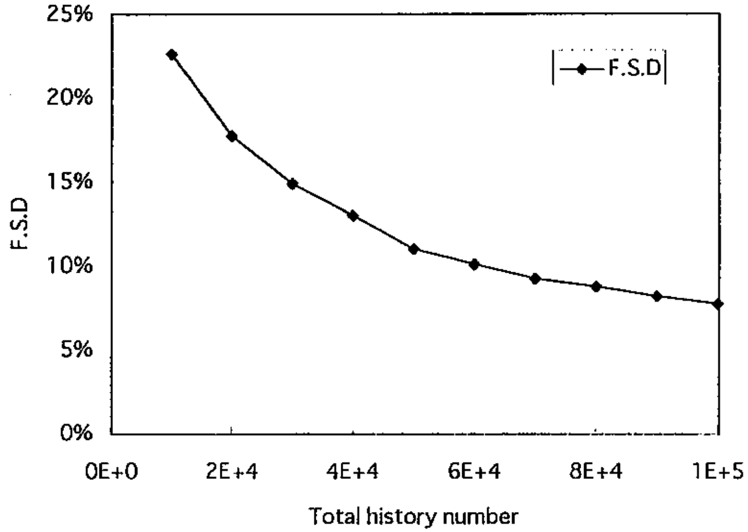

Fig.5.68 F.S.D vs. total history number for Case1_d5_fnrc

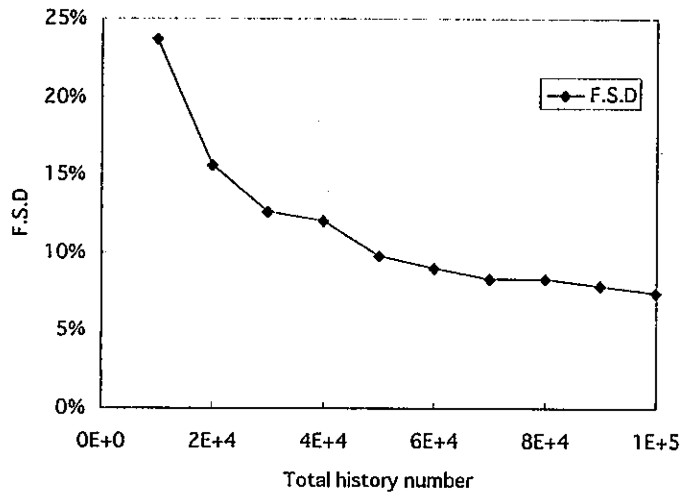

Fig.5.69 F.S.D vs. total history number for Case5_d1

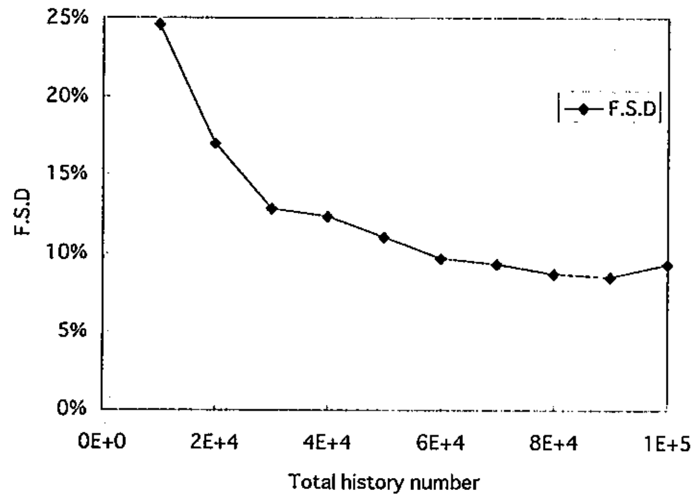

Fig.5.70 F.S.D vs. total history number for Case5_d2

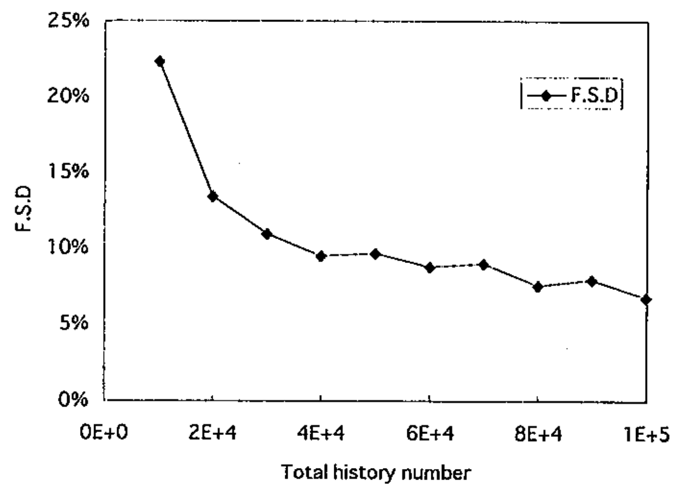

Fig.5.71 F.S.D vs. total history number for Case5_d3

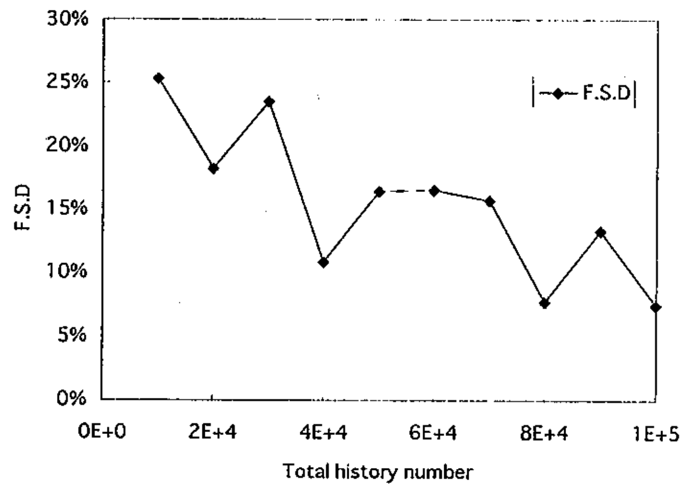

Fig.5.72 F.S.D vs. total history number for Case5_d5

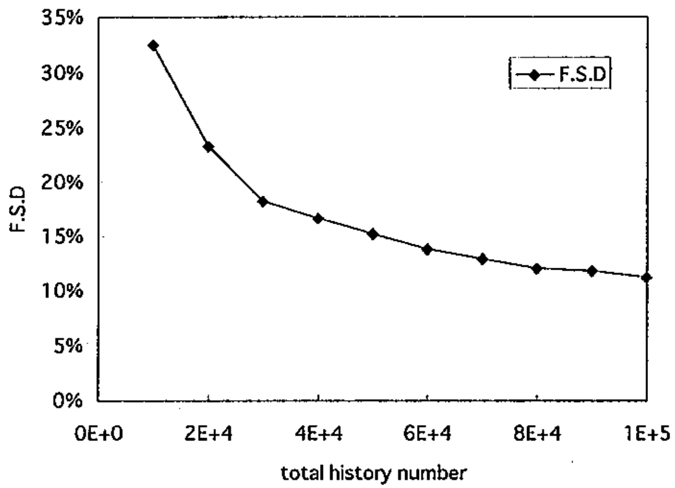

Fig.5.73 F.S.D vs. total history number for Case6_d1

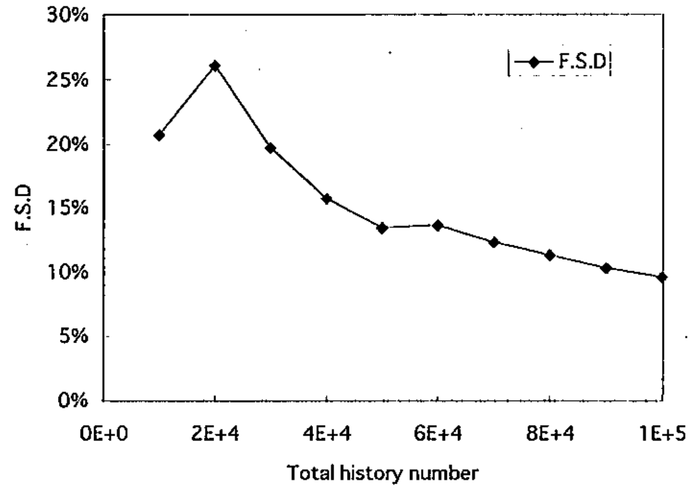

Fig.5.74 F.S.D vs. total history number for Case6_d2

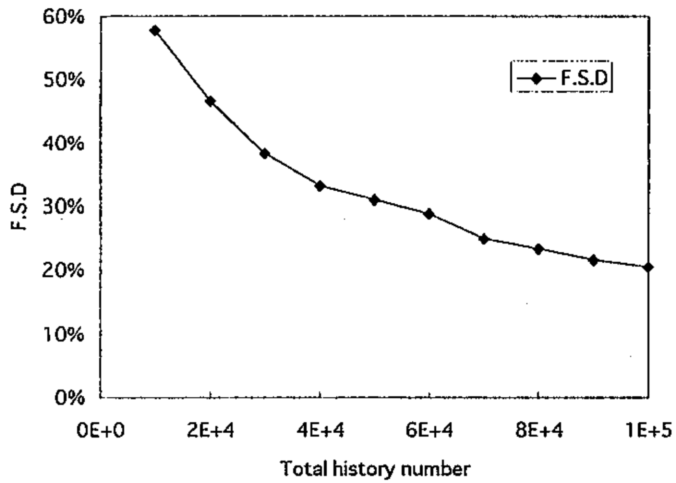

Fig.5.75 F.S.D vs. total history number for Case6_d3

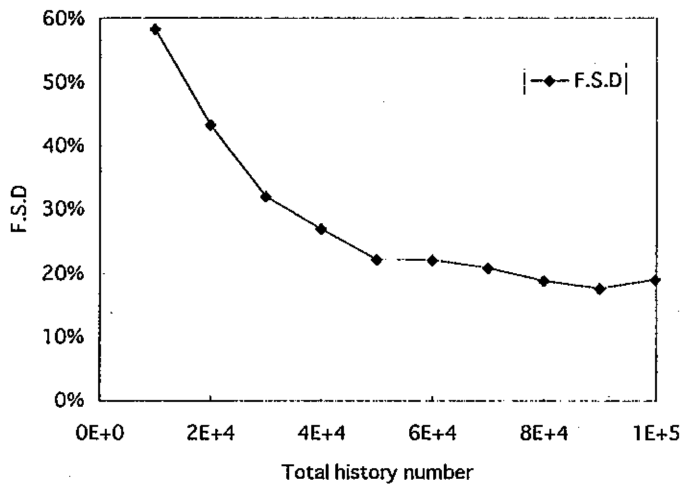

Fig.5.76 F.S.D vs. total history number for Case6_d5

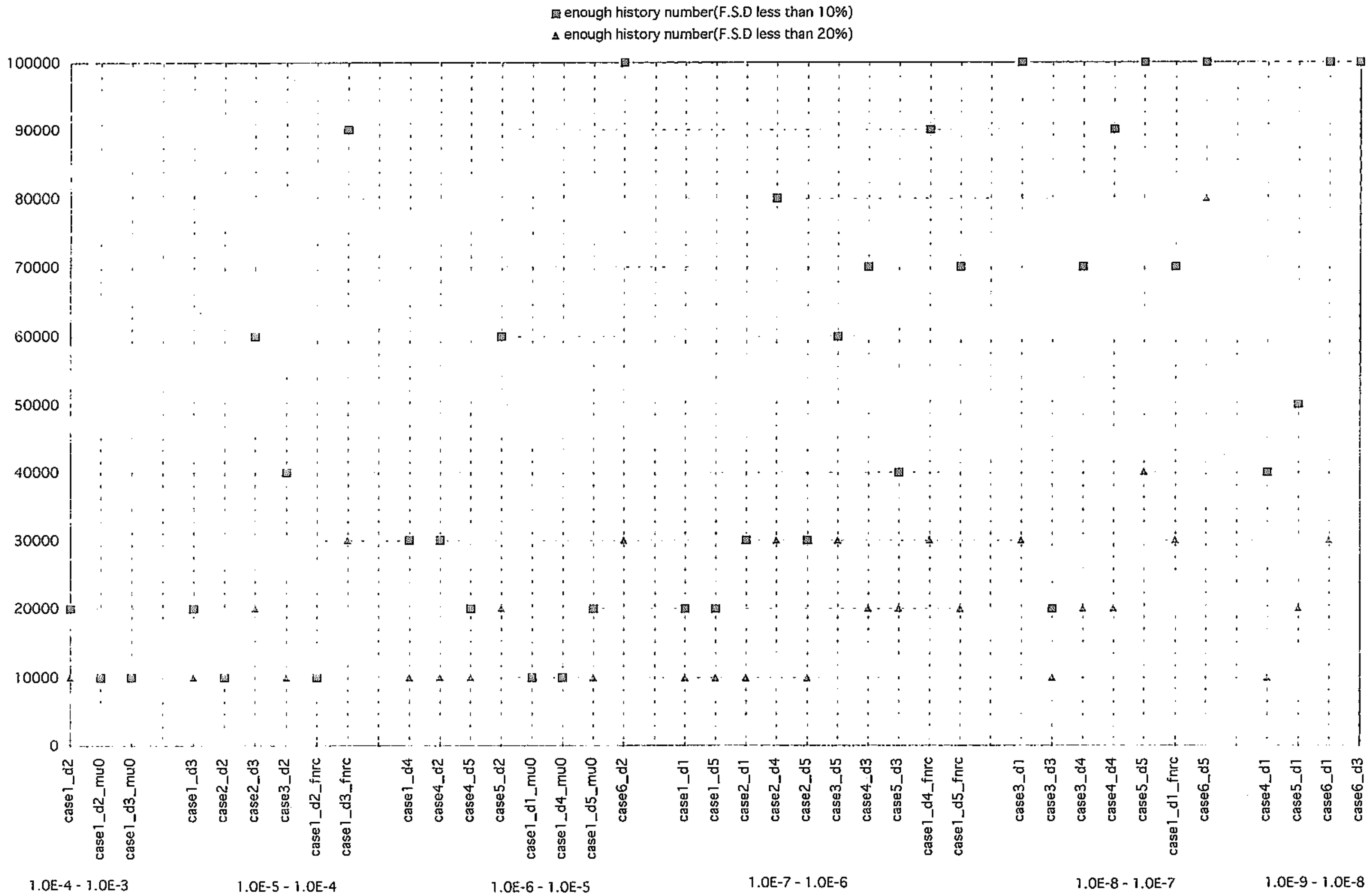

Fig.5.77 Enough history number for all cases

6. New Distance Definition

A more common distance definition was introduced to the PHAMMON code. which can be described as:

$$D_n = \prod_{l=1}^{N_n} \frac{1}{\psi_n^l \cdot T} \qquad n = 1,2, \ldots , N_{cs} \quad \ldots\ldots \quad (23)$$

where N_{cs} , N_n , ψ_n^l are the same as illustrated in eq(16) and T is defined as follows: If the system will make a state transition at $(t+\Delta t)$ given that it is state at time t; and time point $(t+\Delta t)$ will fall in the Ith phase, then $T = T_{P_i} - t$, where T_{P_i} is the end time of the Ith phase.

The plots of failure probability, versus time using by LB method, ME method, Present method and New method are shown in Figure 6.1(a) - 6.38(a), while the plots of f.s.d, versus time are shown in Figure 6.1(b) - 6.38(b). For the failure probability calculation, we do not consider the grace period for the case of all the components are unrepaired.

The numerical results indicate that the new distance definition is an effective means of reducing the variance.

The effects of considering grace period for the case1_d1_mu0 in which all the components unrepaired are as follows:

In case1_d1_mu0, we consider all of the components are unrepaired, this means once the system failed, it can not be recovered. But in the previous calculation, we consider grace period for all cases.

In PHAMMON code, we consider the system failure in the following steps: If the system is in failure state, we compare the time duration with grace period; if the time duration is larger then grace period, then end of this history; but if time duration is less then grace period, we will sample a failed component (for the case of all of the components are unrepaired). Certainly, this sampling will be accompanied by a weight, and the value of the weight is depended on the adopted technique (LB method, ME method, Present work and New method). This is the reason why even for the demand failure sampling, the f.s.d is different among each method.

Moreover, There is five kinds of failure criteria (D1 to D5) for each Case. The failure criteria of D1(All loops are available) is most stringent among all these five failure criteria, i.e. the effective history number for the demand sampling in case D1 is less than that in case D2, D3, D4 and D5. On the other hand, the weight created by using New method is changed relatively great compared with that created by using Present method.

So the result of f.s.d in case1_d1_mu0 can be effected by following factors:
1) we consider the grace period for the case in which all of the components are unrepaired;
2) case D1 has less effective history number compared with other cases;
3) by using New method, the weight is changed relatively great.

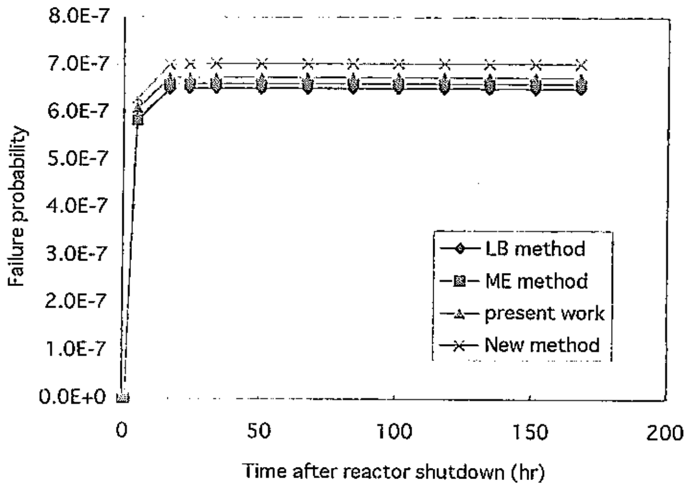

Fig.6.1a Failure probability for case1_d1

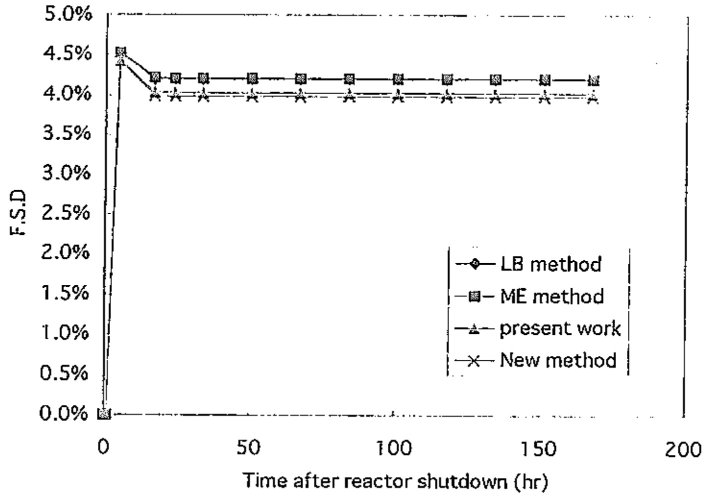

Fig.6.1b Comparison of f.s.d results for case1_d1

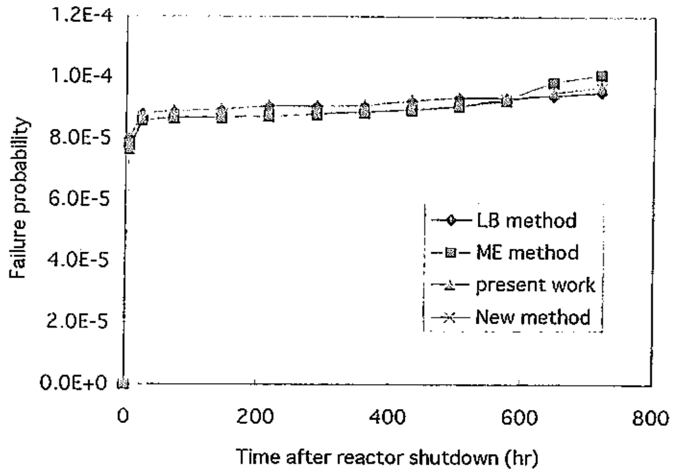

Fig.6.2a Failure probability for case1_d2

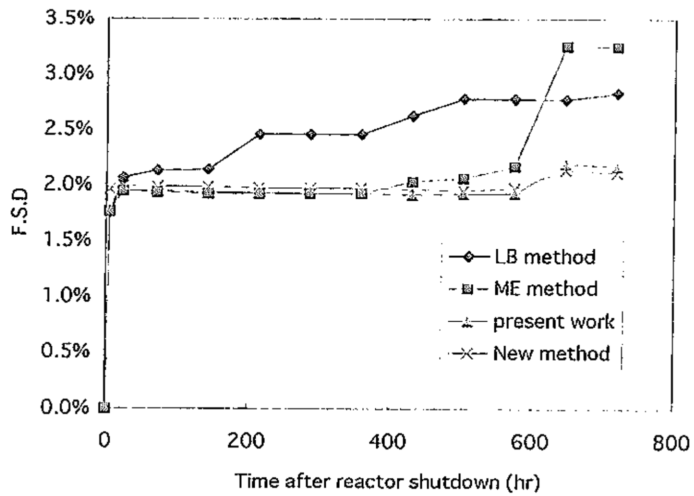

Fig.6.2b Comparison of f.s.d results for case1_d2

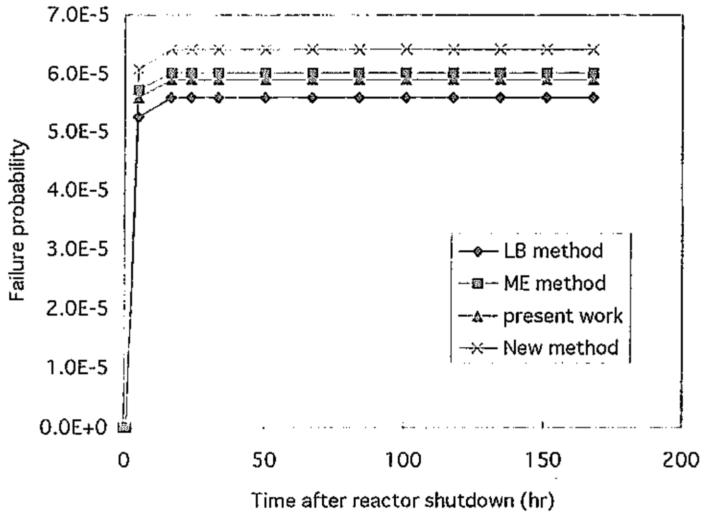

Fig.6.3a Failure probability for case1_d3

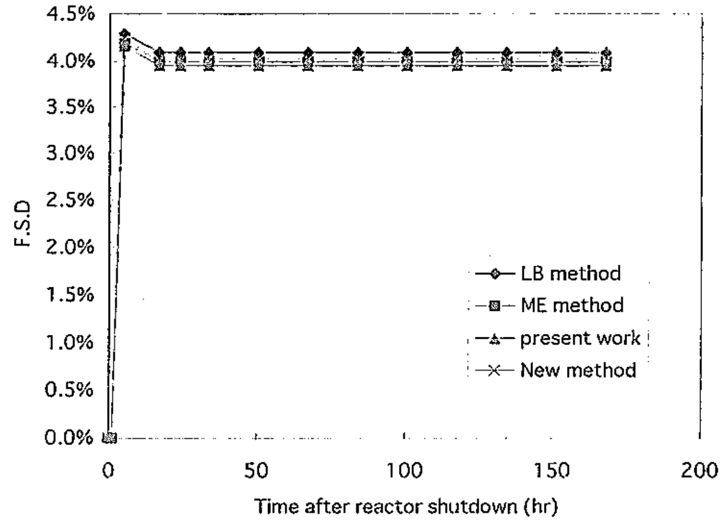

Fig.6.3b Comparison of f.s.d results for case1_d3

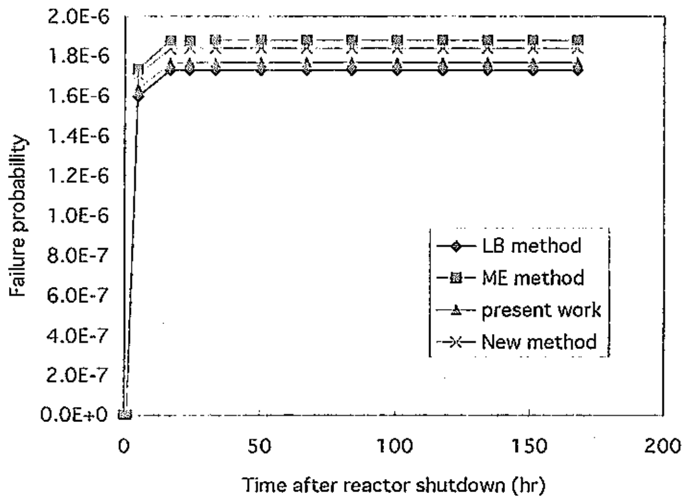

Fig.6.4a Failure probability for case1_d4

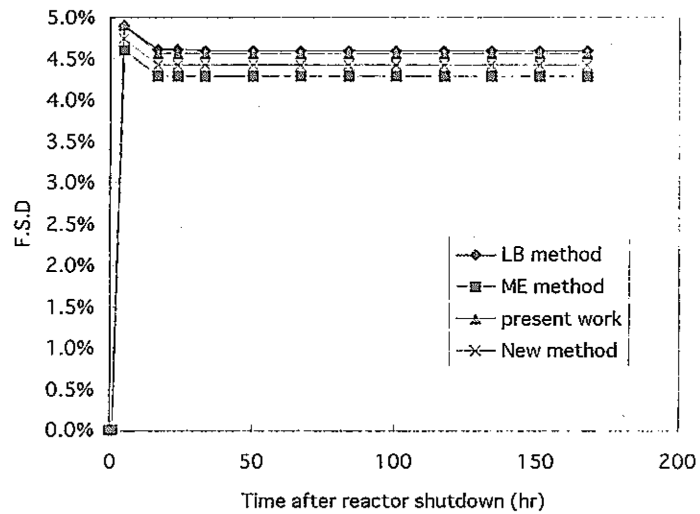

Fig.6.4b Comparison of f.s.d results for case1_d4

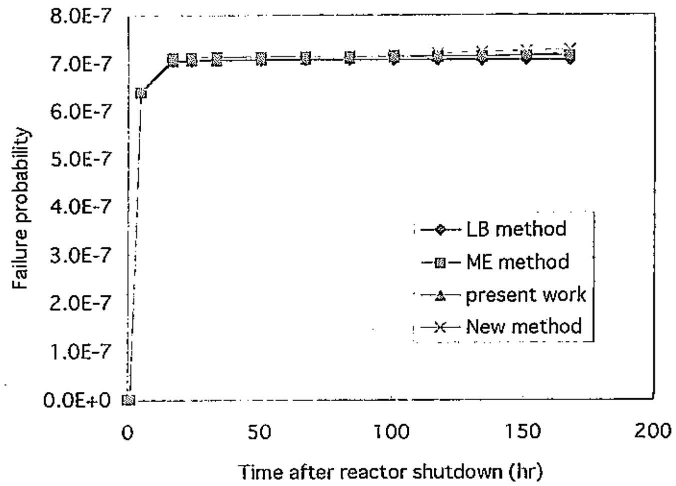

Fig.6.5a Failure probability for case1_d5

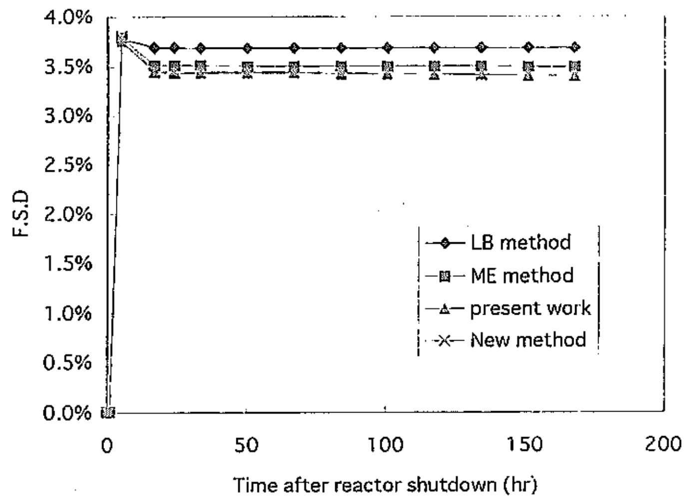

Fig.6.5b Comparison of f.s.d results for case1_d5

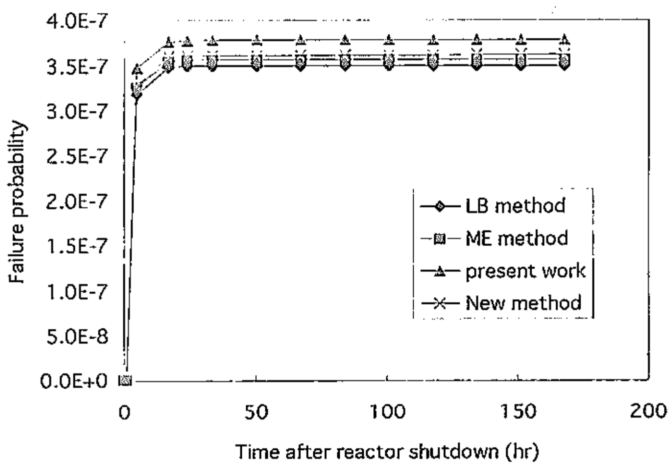

Fig.6.6a Failure probability for case2_d1

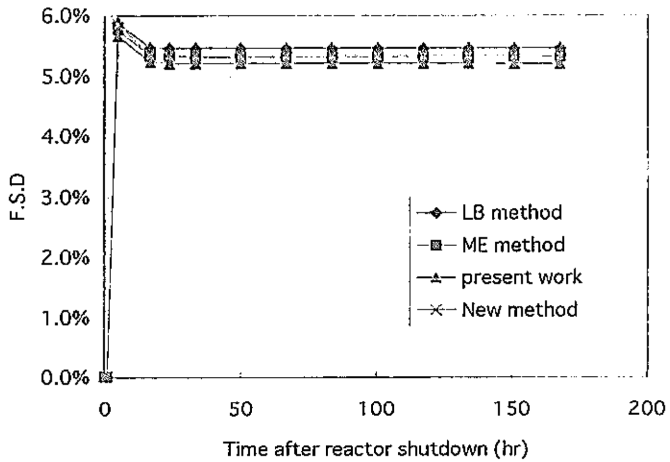

Fig.6.6b Comparison of f.s.d results for case2_d1

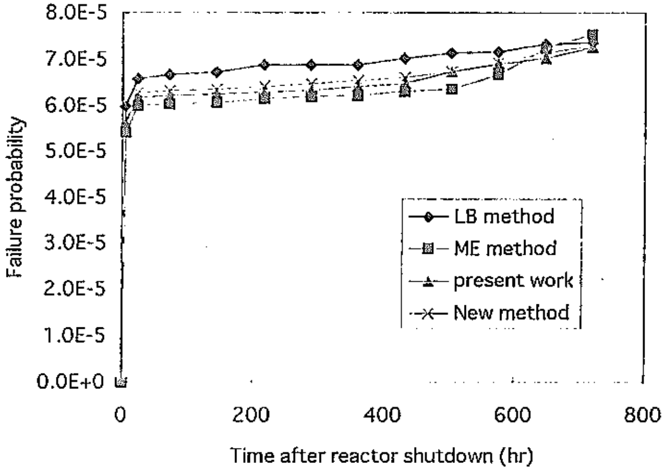

Fig.6.7a Failure probability for case2_d2

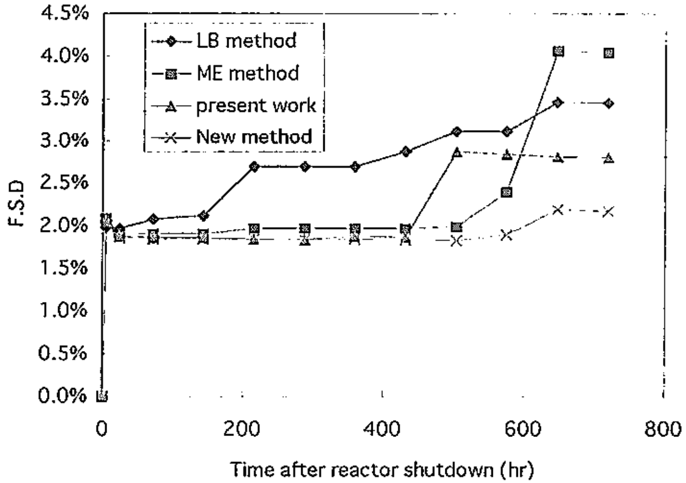

Fig.6.7b Comparison of f.s.d results for case2_d2

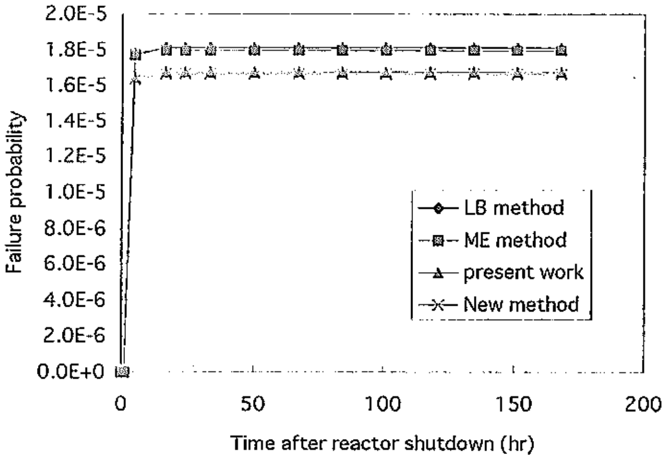

Fig.6.8a Failure probability for case2_d3

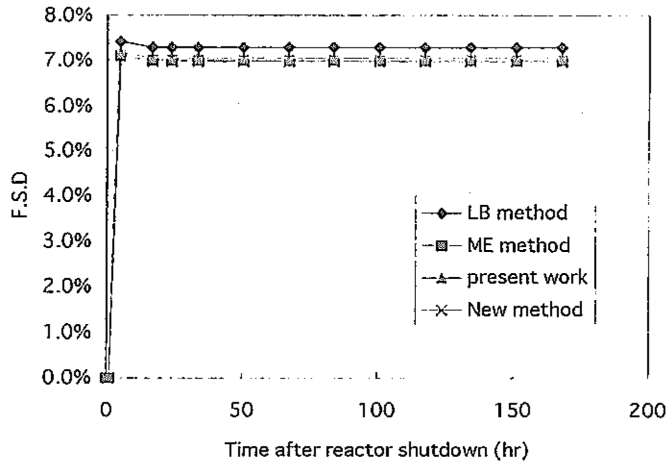

Fig.6.8b Comparison of f.s.d results for case2_d3

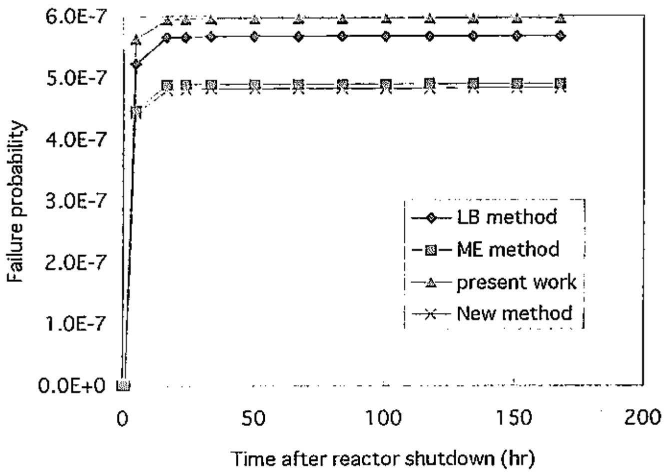

Fig.6.9a Failure probability for case2_d4

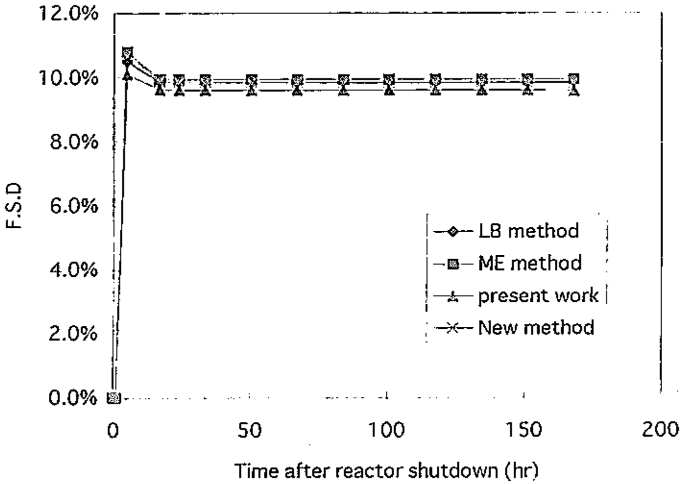

Fig.6.9b Comparison of f.s.d results for case2_d4

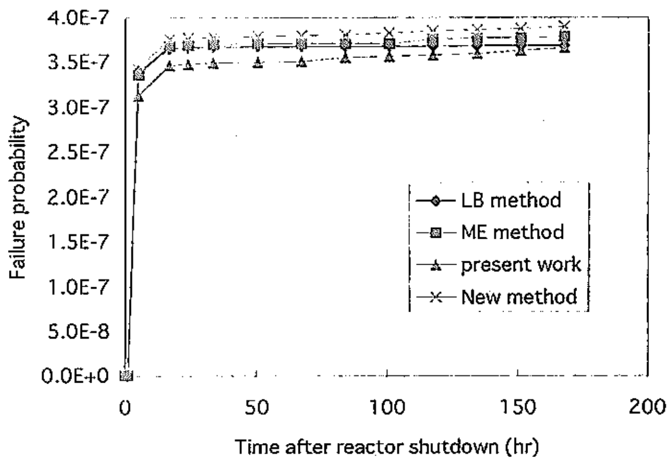

Fig.6.10a Failure probability for case2_d5

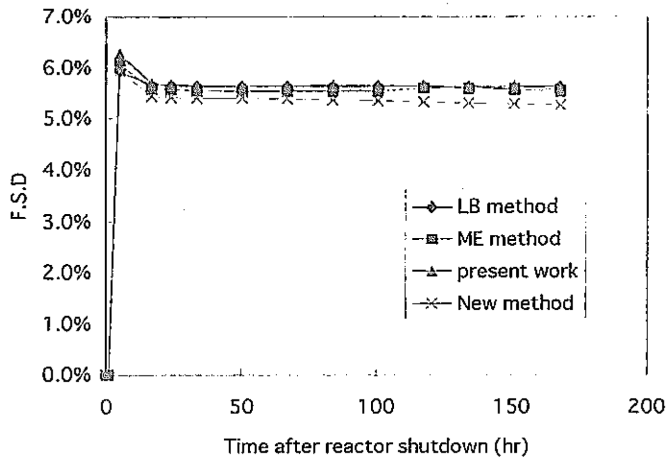

Fig.6.10b Comparison of f.s.d results for case2_d5

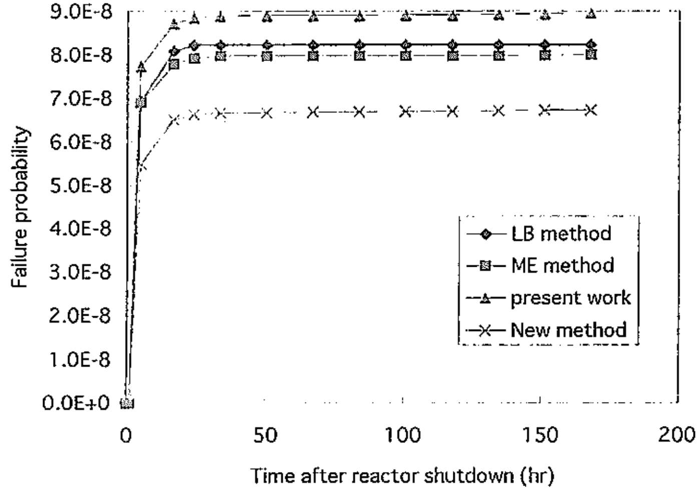

Fig.6.11a Failure probability for case3_d1

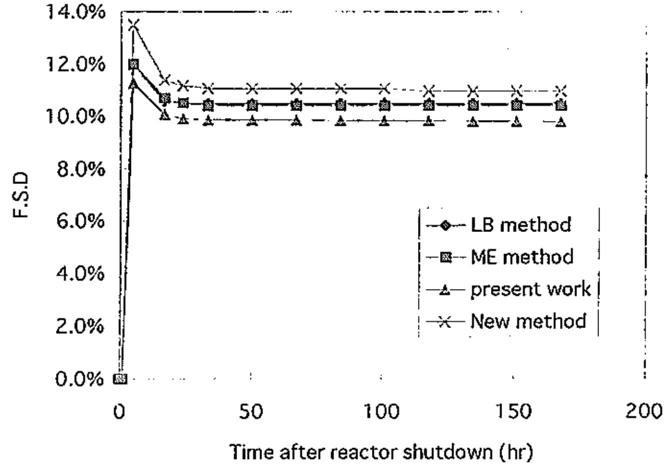

Fig.6.11b Comparison of f.s.d results for case3_d1

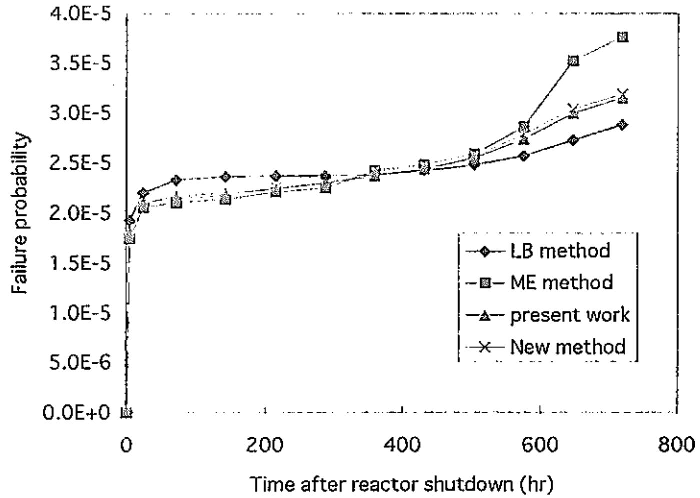

Fig.6.12a Failure probability for case3_d2

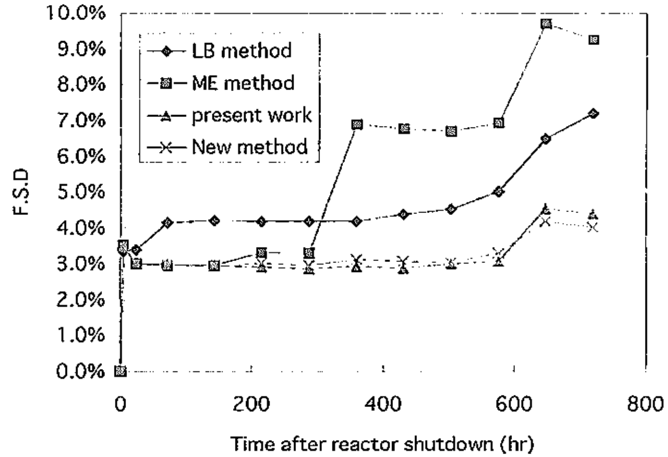

Fig.6.12b Comparison of f.s.d results for case3_d2

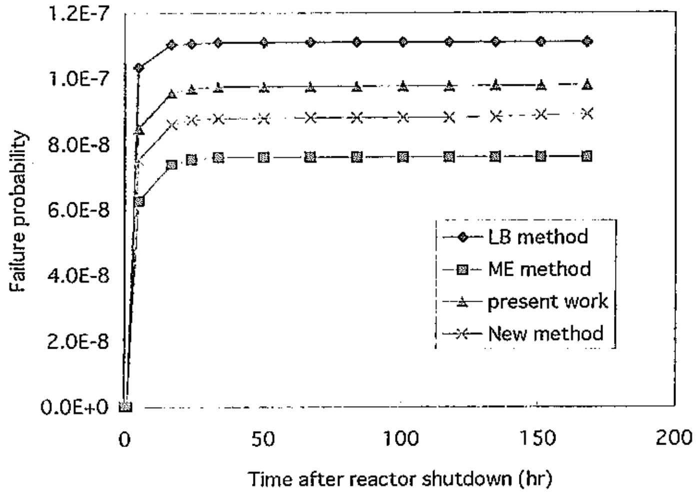

Fig.6.13a Failure probability for case3_d3

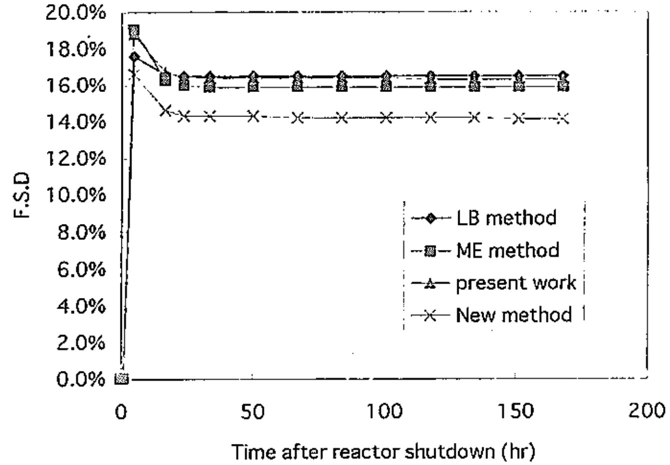

Fig.6.13b Comparison of f.s.d results for case3_d3

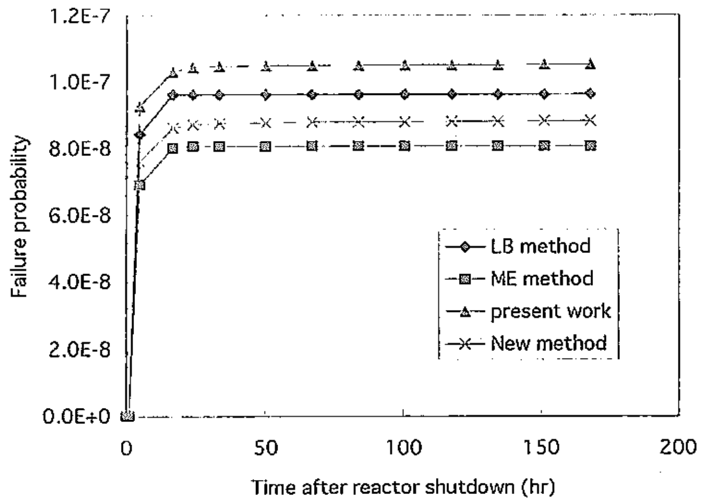

Fig.6.14a Failure probability for case3_d4

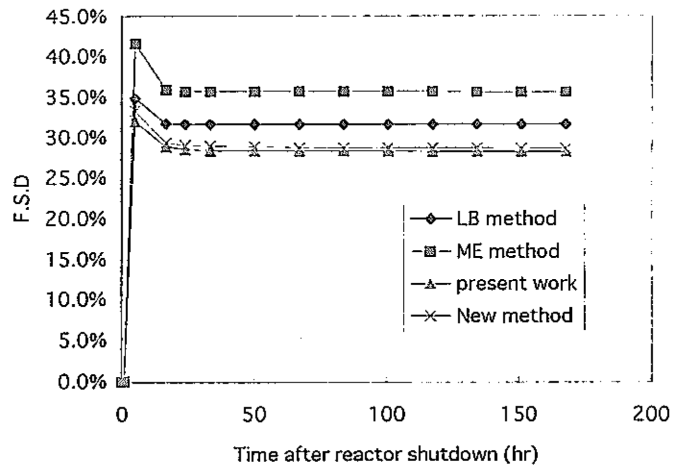

Fig.6.14b Comparison of f.s.d results for case3_d4

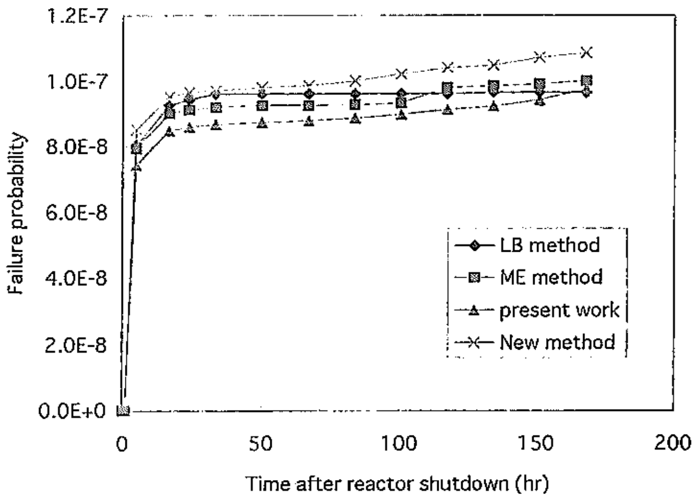

Fig.6.15a Failure probability for case3_d5

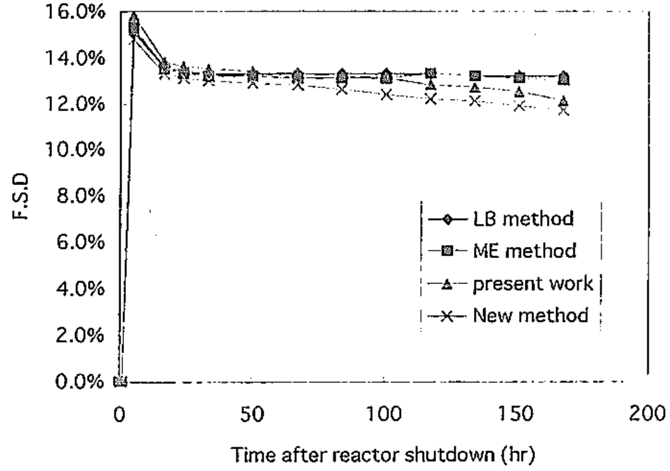

Fig.6.15b Comparison of f.s.d results for case3_d5

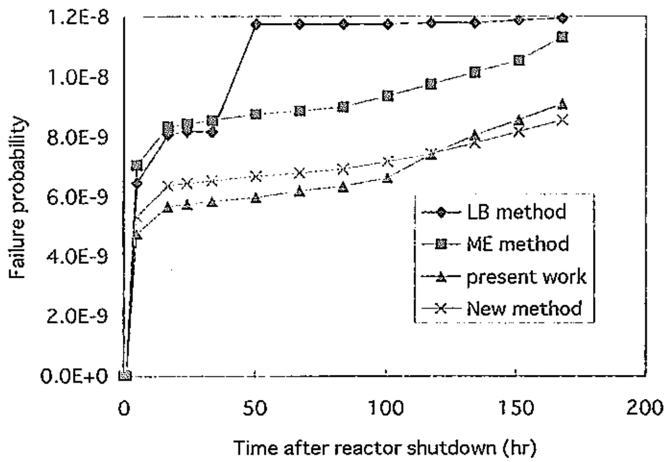

Fig.6.16a Failure probability for case4_d1

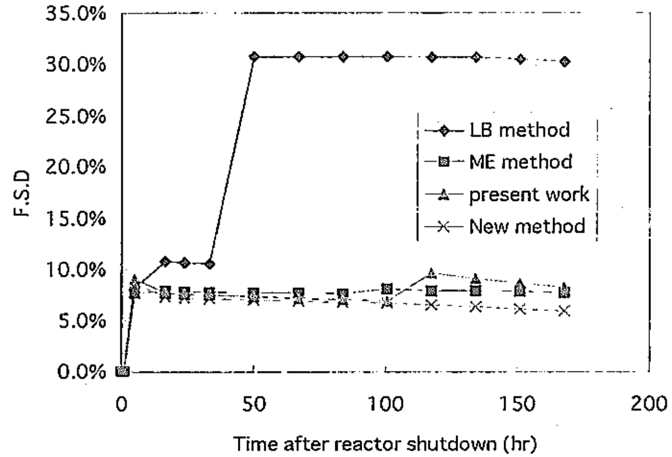

Fig.6.16b Comparison of f.s.d results for case4_d1

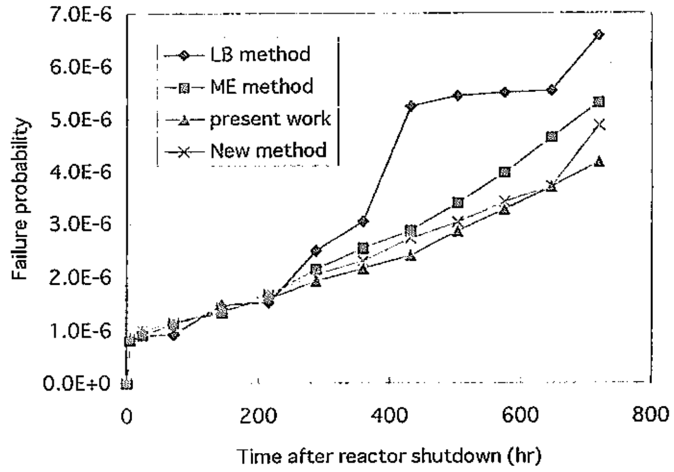

Fig.6.17a Failure probability for case4_d2

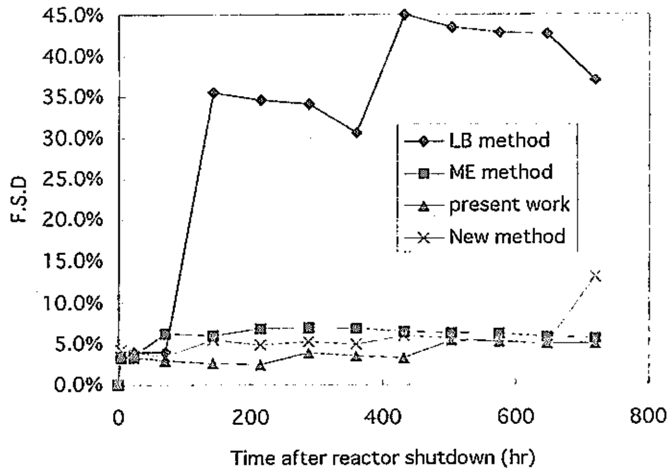

Fig.6.17b Comparison of f.s.d results for case4_d2

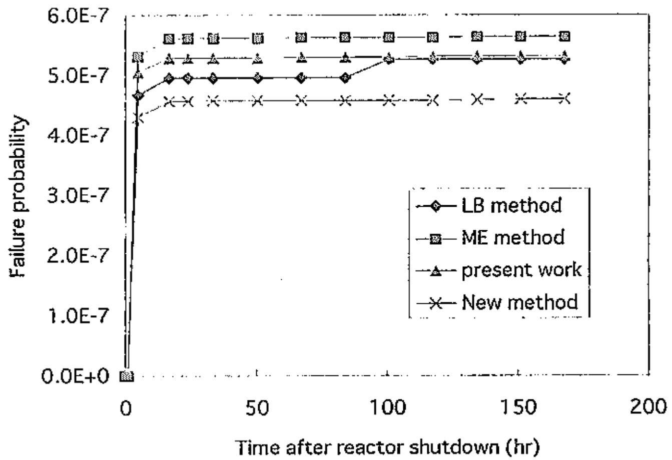

Fig.6.18a Failure probability for case4_d3

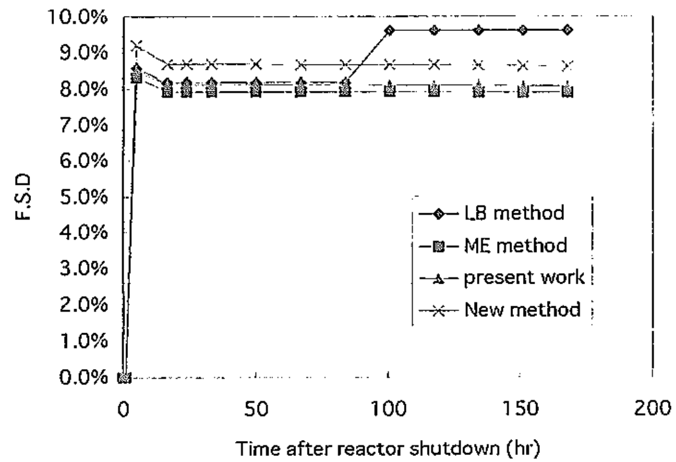

Fig.6.18b Comparison of f.s.d results for case4_d3

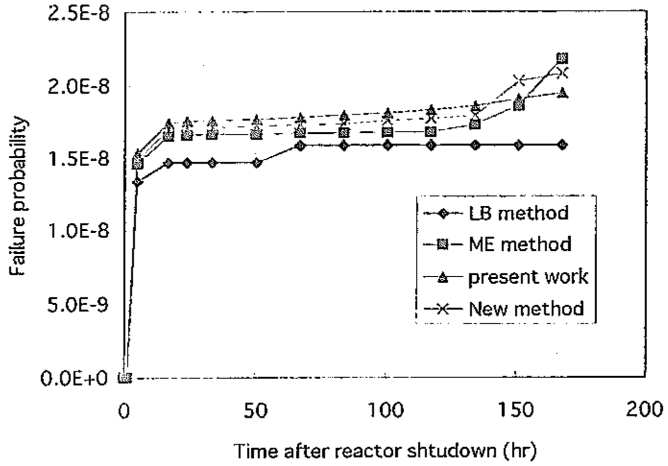

Fig.6.19a Failure probability for case4_d4

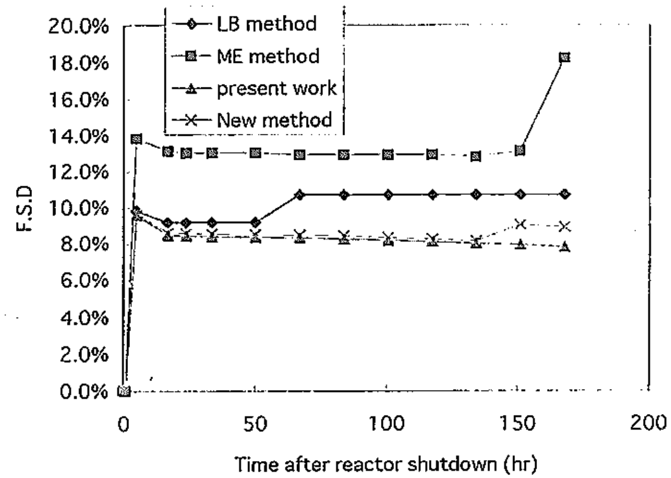

Fig.6.19b Comparison of f.s.d results for case4_d4

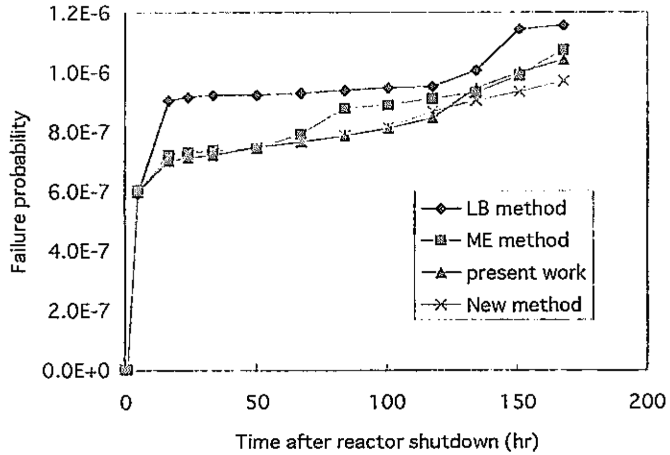

Fig.6.20a Failure probability for case4_d5

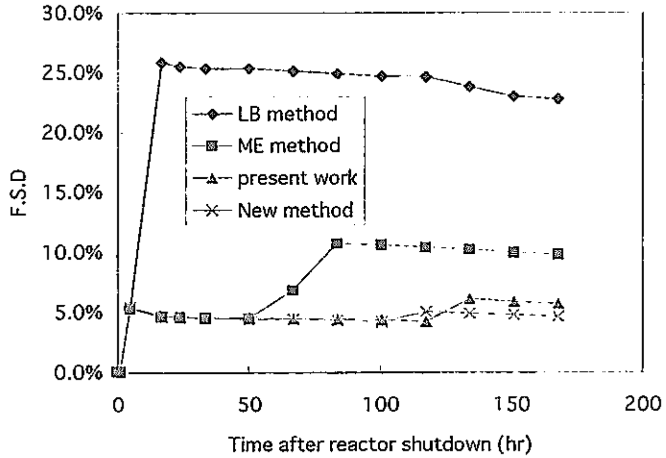

Fig.6.20b Comparison of f.s.d results for case4_d5

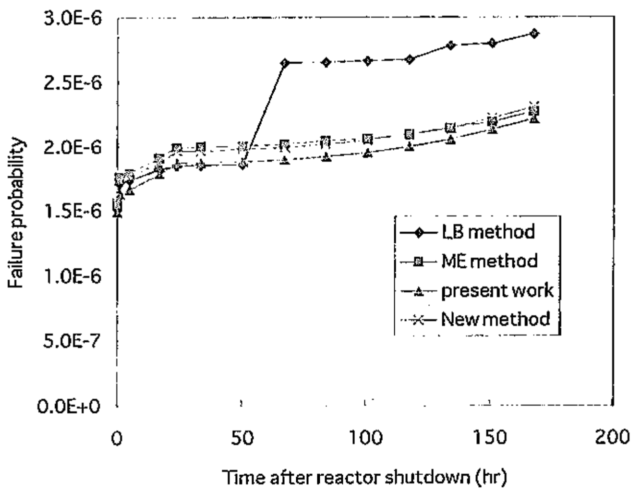

Fig.6.21a Failure probability for case1_d1_mu0

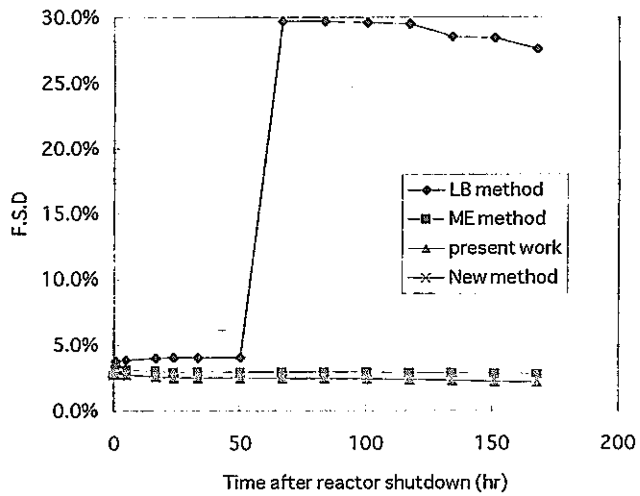

Fig.6.21b Comparison of f.s.d results for case1_d1_mu0

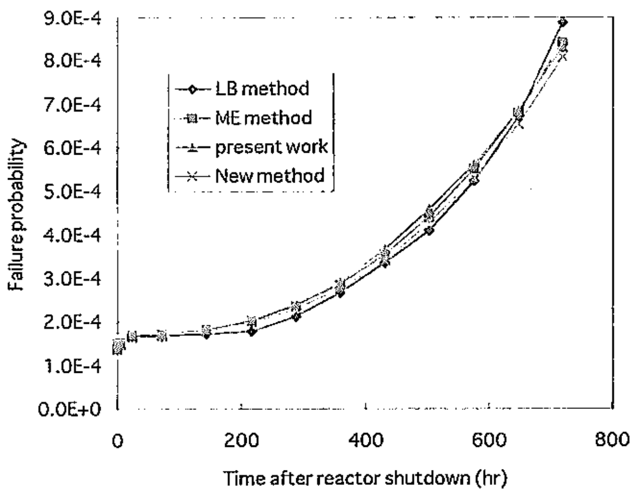

Fig.6.22a Failure probability for case1_d2_mu0

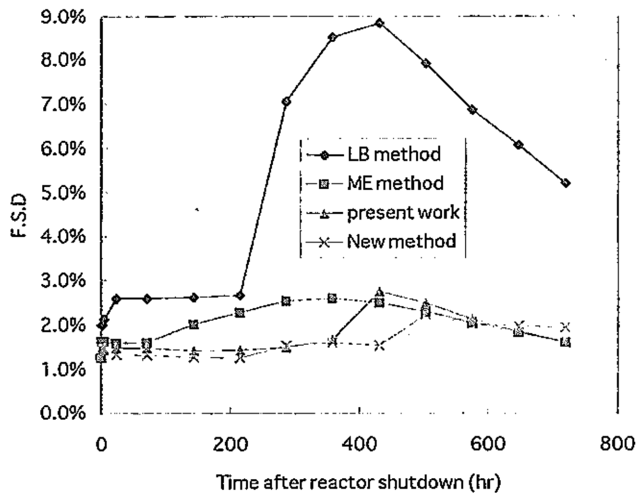

Fig.6.22b Comparison of f.s.d results for case1_d2_mu0

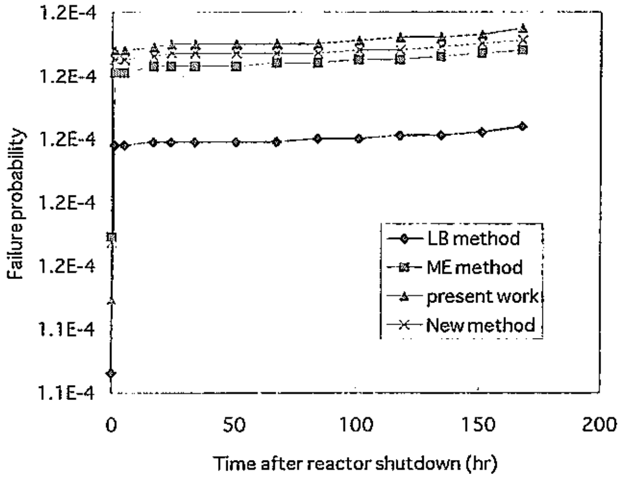

Fig6.23a Failure probability for case1_d3_mu0

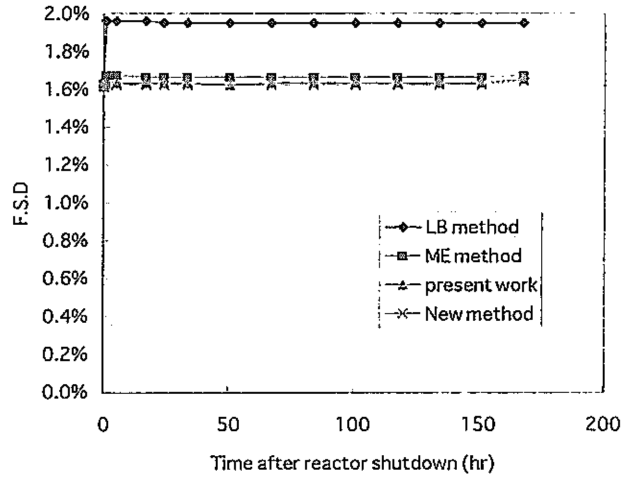

Fig.6.23b Comparison of f.s.d results for case1_d3_mu0

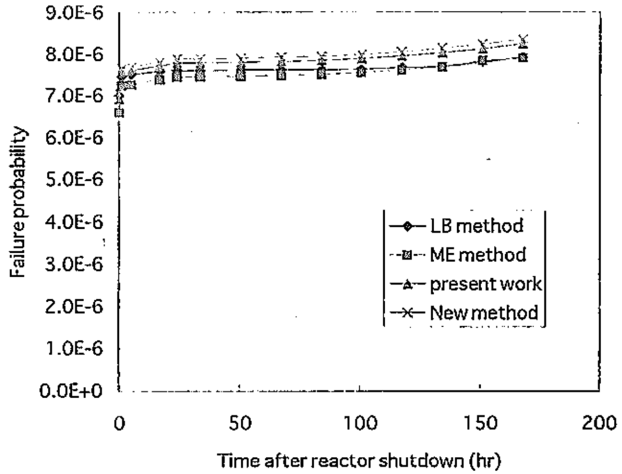

Fig.6.24a Failure probability for case1_d4_mu0

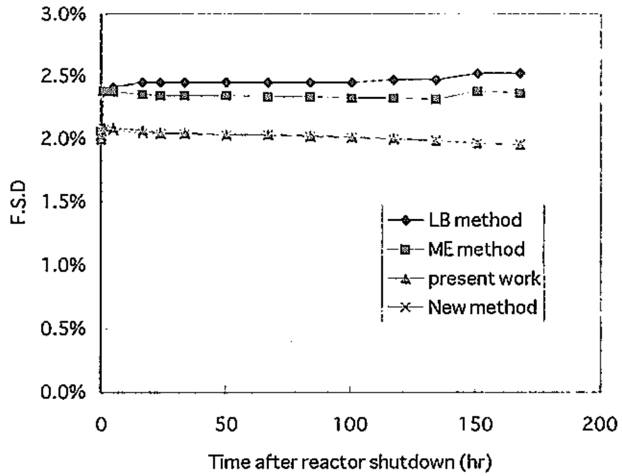

Fig.6.24b Comparison of f.s.d results for case1_d4_mu0

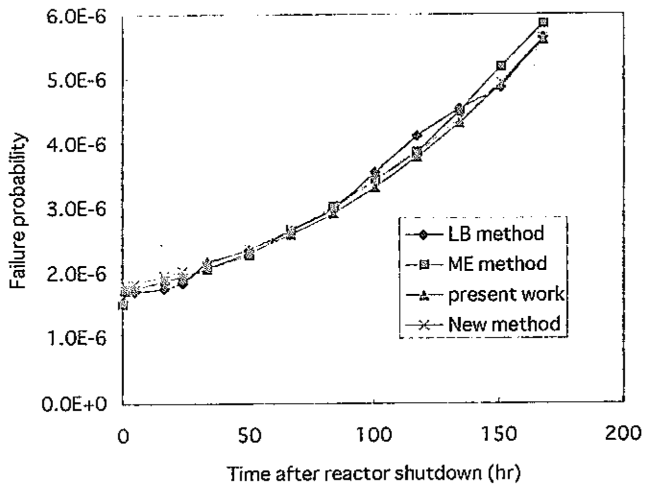

Fig.6.25a Failure probability for case1_d5_mu0

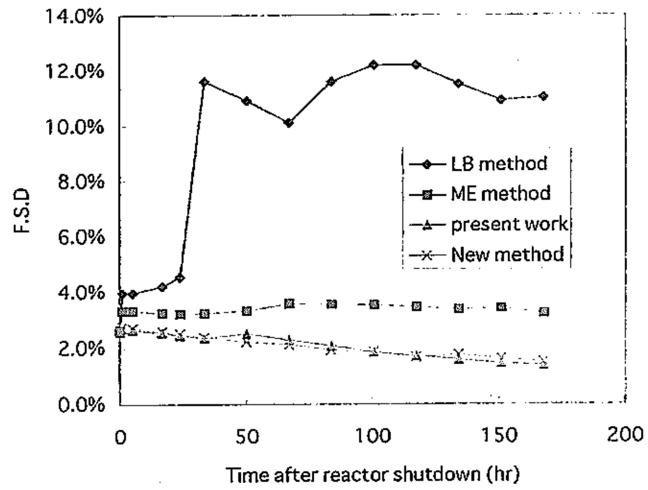

Fig.6.25b Comparison of f.s.d results for case1_d5_mu0

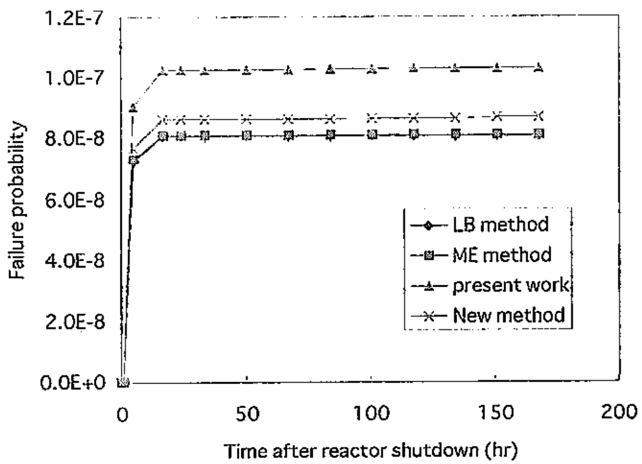

Fig.6.26a Failure probability for case1_d1_fnrc

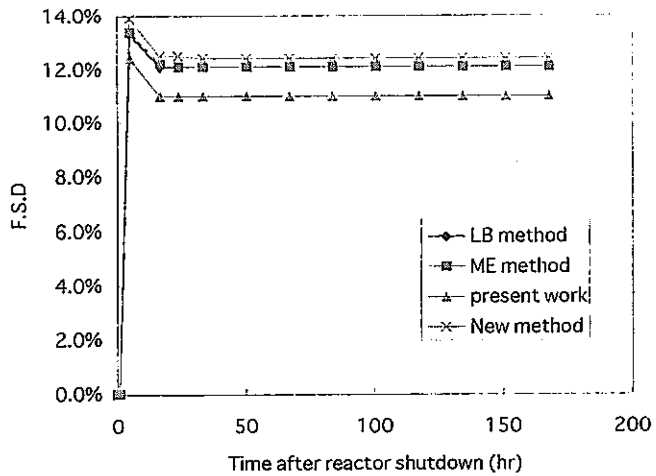

Fig.6.26b Comparison of f.s.d results for case1_d1_fnrc

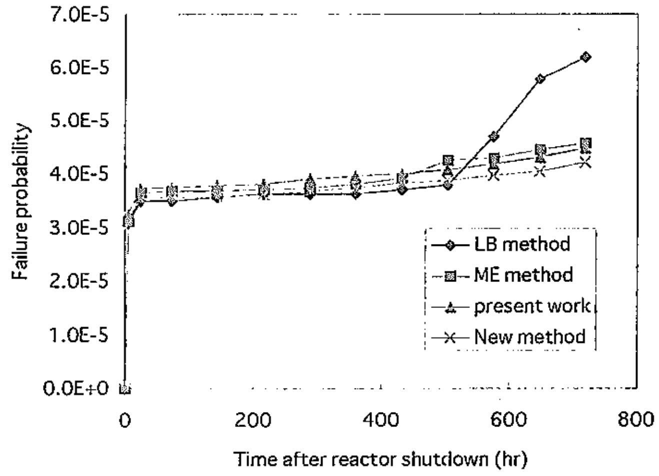

Fig.6.27a Failure probability for case1_d2_fnrc

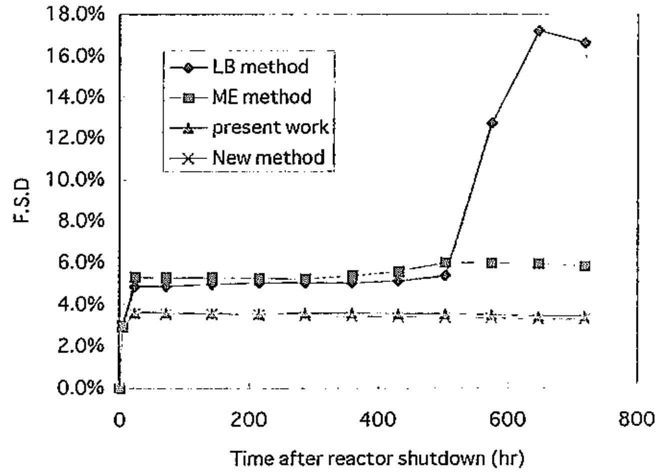

Fig.6.27b Comparison of f.s.d results for case1_d2_fnrc

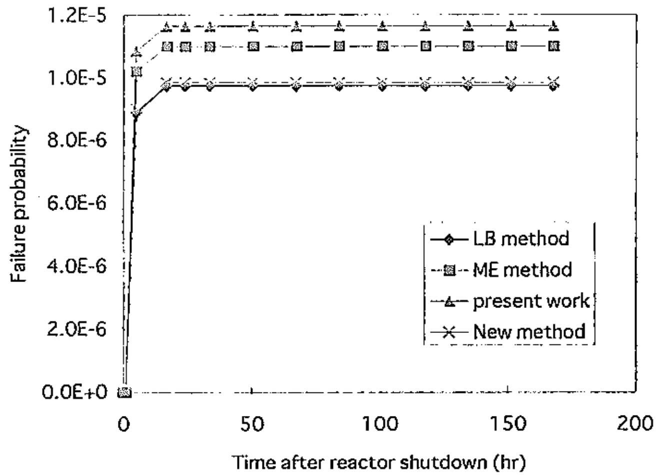

Fig.6.28a Failure probability for case1_d3_fnrc

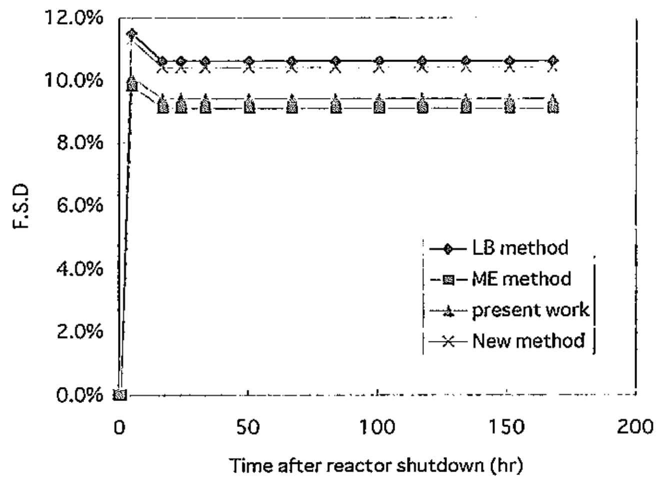

Fig.6.28b Comparison of f.s.d results for case1_d3_fnrc

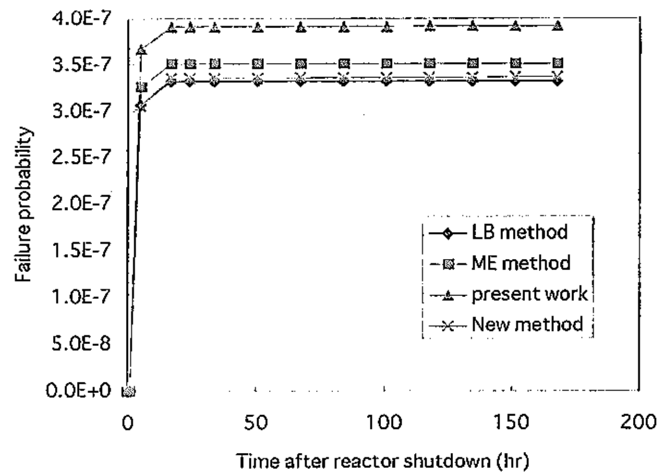

Fig.6.29a Failure probability for case1_d4_fnrc

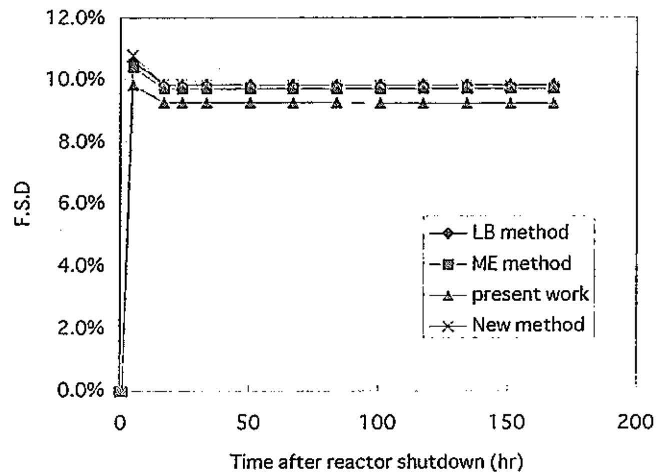

Fig.6.29b Comparison of f.s.d results for case1_d4_fnrc

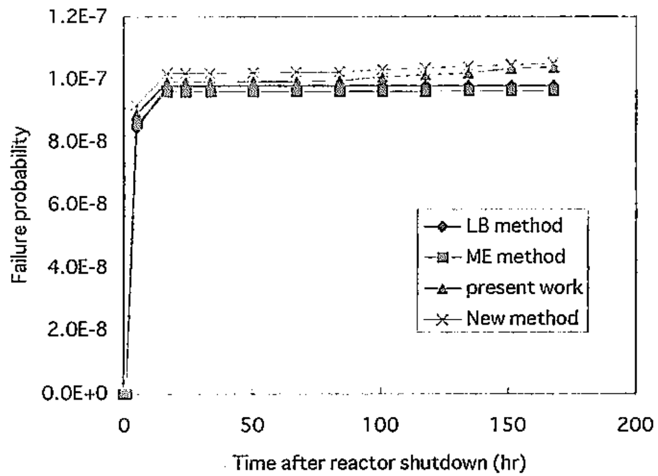

Fig.6.30a Failure probability for case1_d5_fnrc

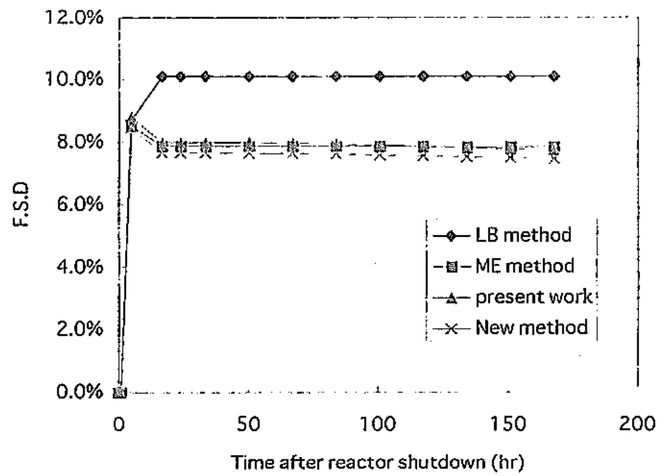

Fig.6.30b Comparison of f.s.d results for case1_d5_fnrc

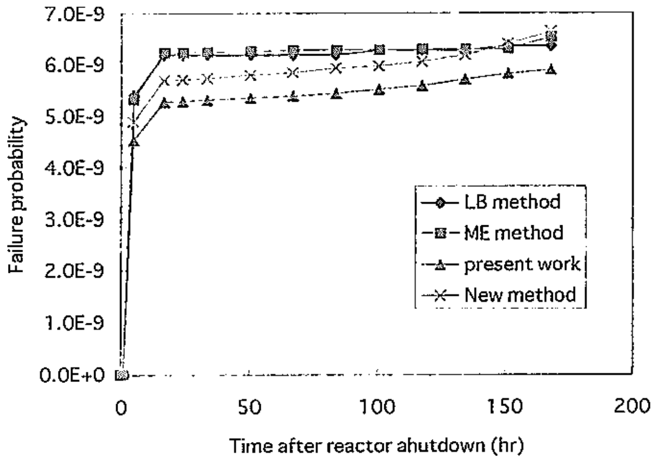

Fig.6.31a Failure probability for case5_d1

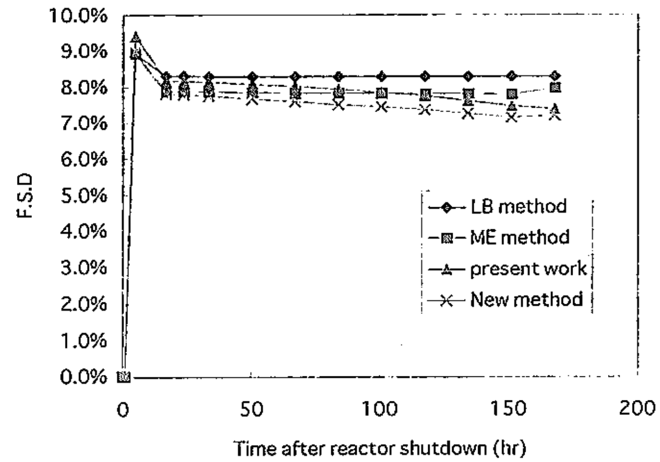

Fig.6.31b Comparison of f.s.d results for case5_d1

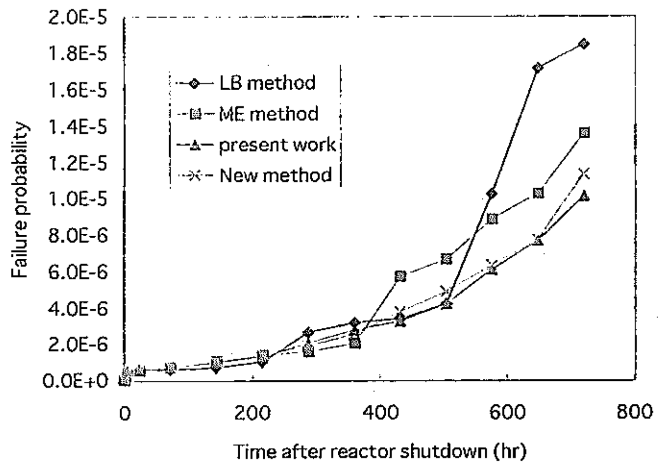

Fig.6.32a Failure probability for case5_d2

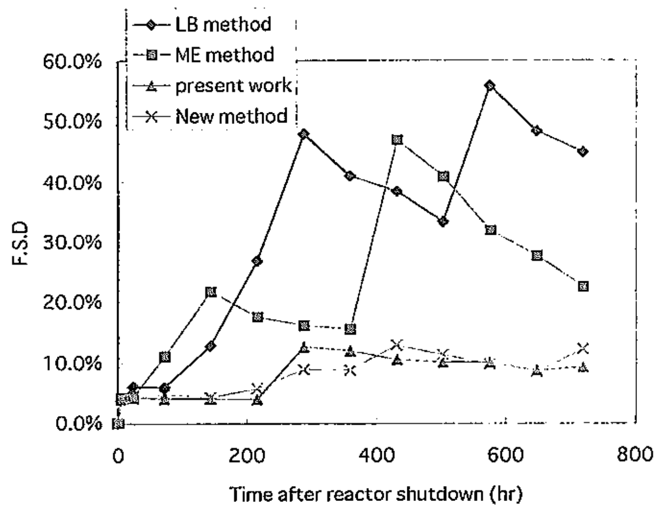

Fig.6.32b Comparison of f.s.d results for case5_d2

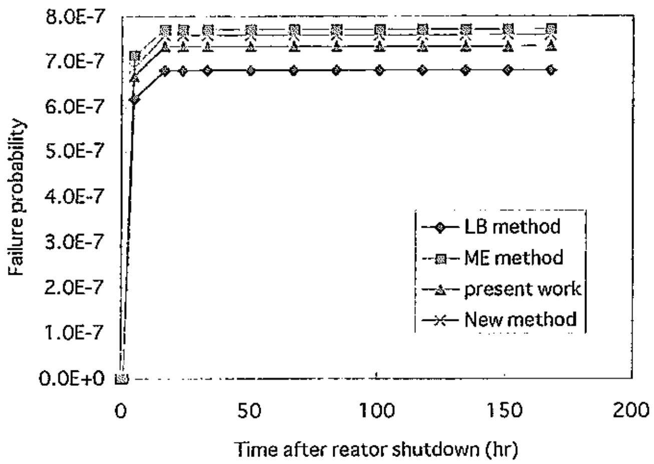

Fig.6.33a Failure probability for case5_d3

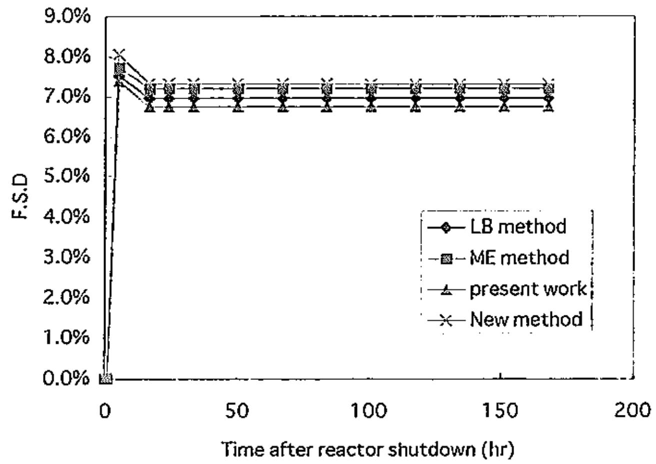

Fig.6.33b Comparison of f.s.d results for case5_d3

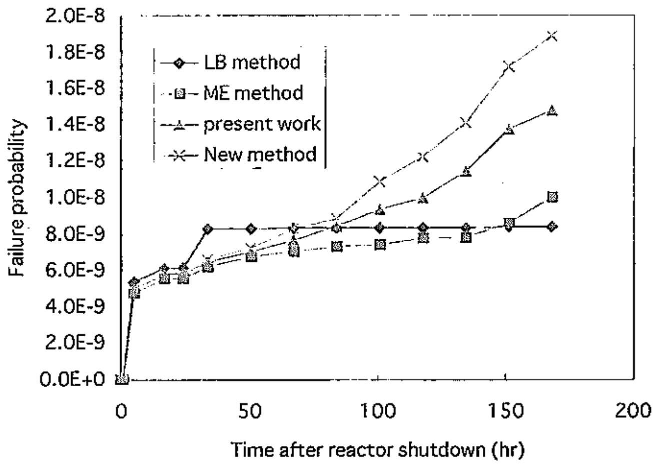

Fig.6.34a Failure probability for case5_d5

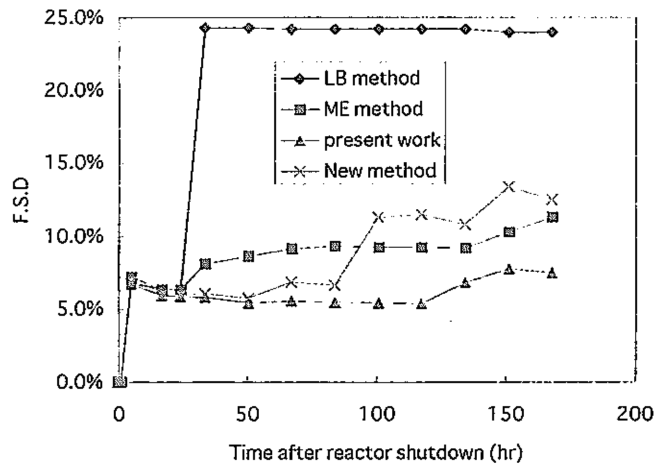

Fig.6.34b Comparison of f.s.d results for case5_d5

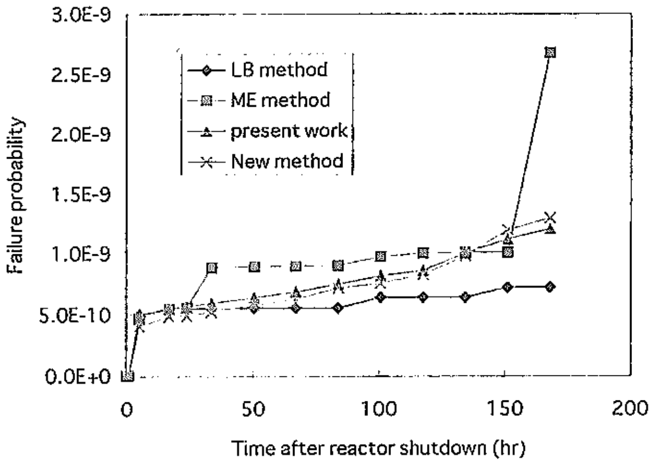

Fig.6.35a Failure probability for case6_d1

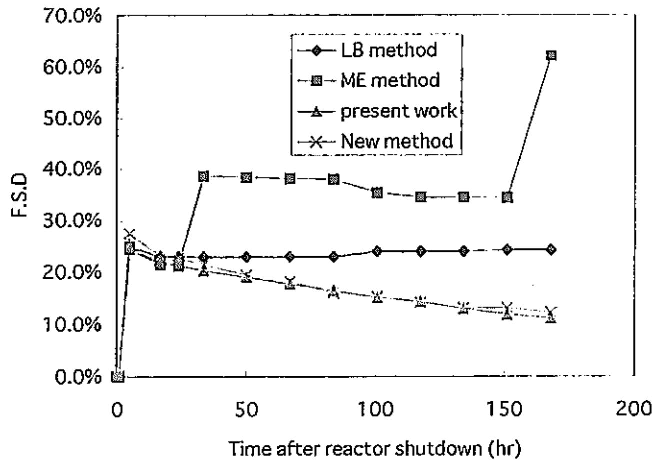

Fig.6.35b Comparison of f.s.d results for case6_d1

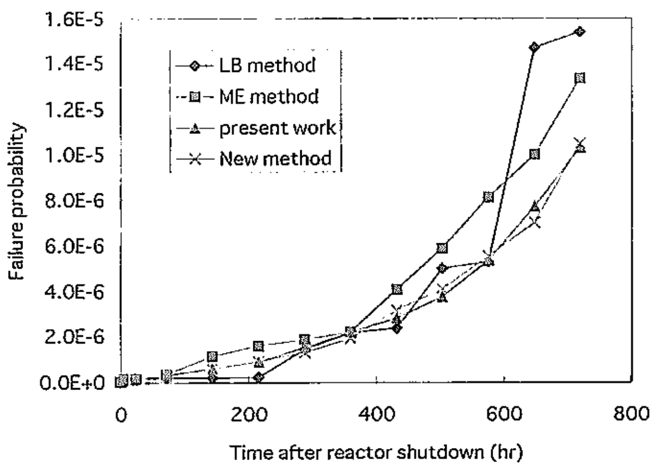

Fig.6.36a Failure probability for case6_d2

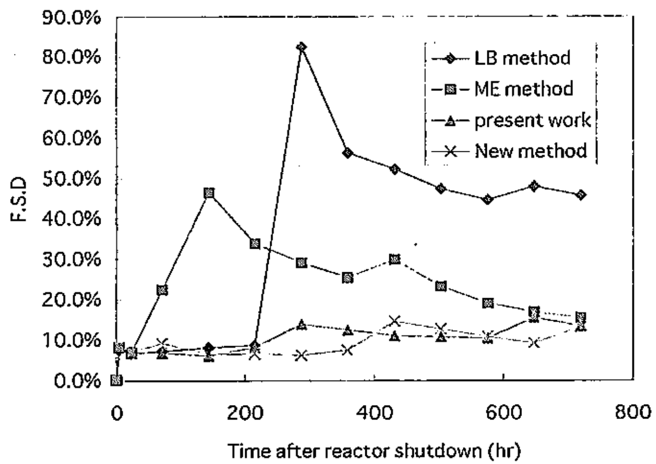

Fig.6.36b Comparison of f.s.d results for case6_d2

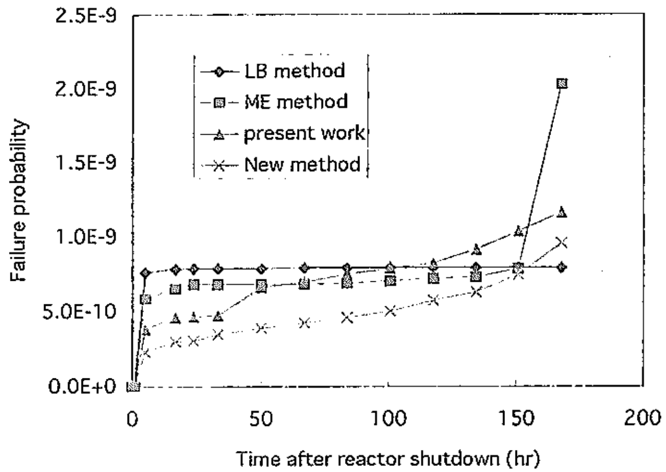

Fig.6.37a Failure probability for case6_d3

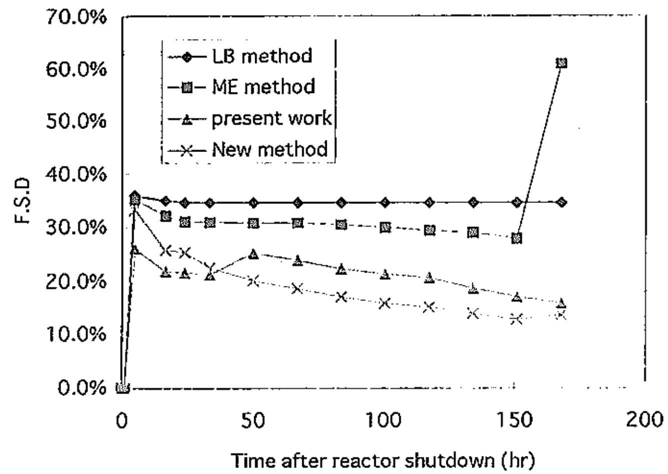

Fig.6.37b Comparison of f.s.d results for case6_d3

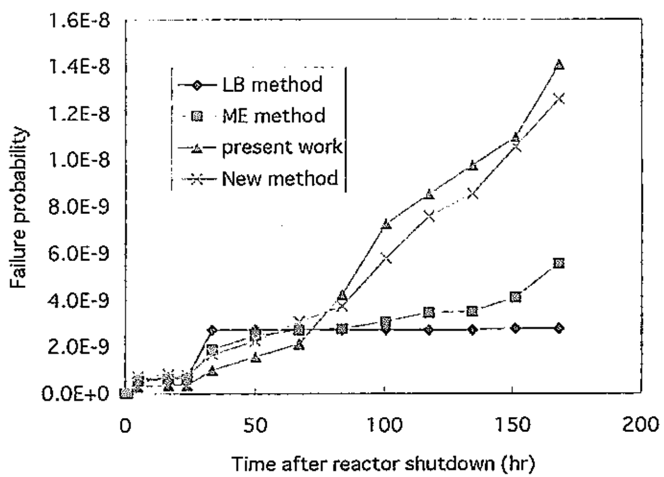

Fig.6.38a Failure probability for case6_d5

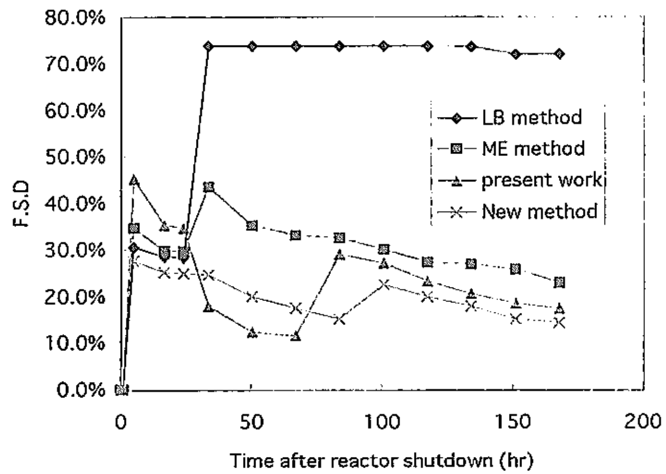

Fig.6.38b Comparison of f.s.d results for case6_d5

6. Conclusions

Reliability and availability analysis usually deals with highly reliable systems, which have very low probability of failure. Therefore the variance reduction method is needed to improve the computational efficiency of the Monte Carlo simulation. In this work, we applied another variance reduction method to the PHAMMON code by introducing a concept of distance. Compared with the original method, the results show that the use of the biasing of the transitions towards the closest cut set can further decrease variance and is highly effective.

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