

軽水炉保全最適化のための統合シミュレータ Dr. Mainte

Dr. Mainte:
Integrated Simulator
for Maintenance Optimization of LWRs

磯部 仁博
Yoshihiro Isobe
原子燃料工業株式会社
Nuclear Fuel Industries Ltd.

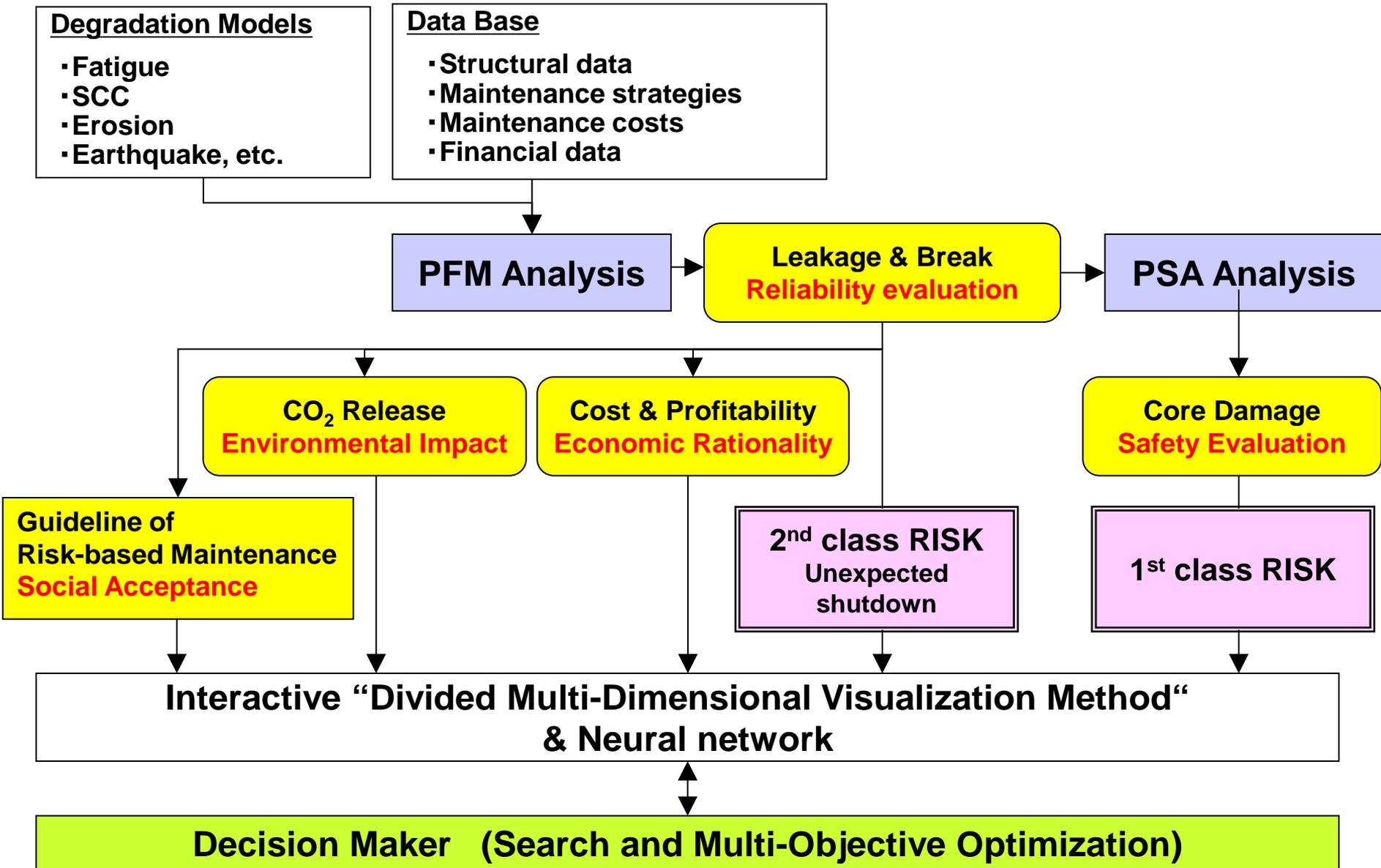
吉村 忍
Shinobu Yoshimura
国立大学法人 東京大学
The University of Tokyo

■ Background and Objectives

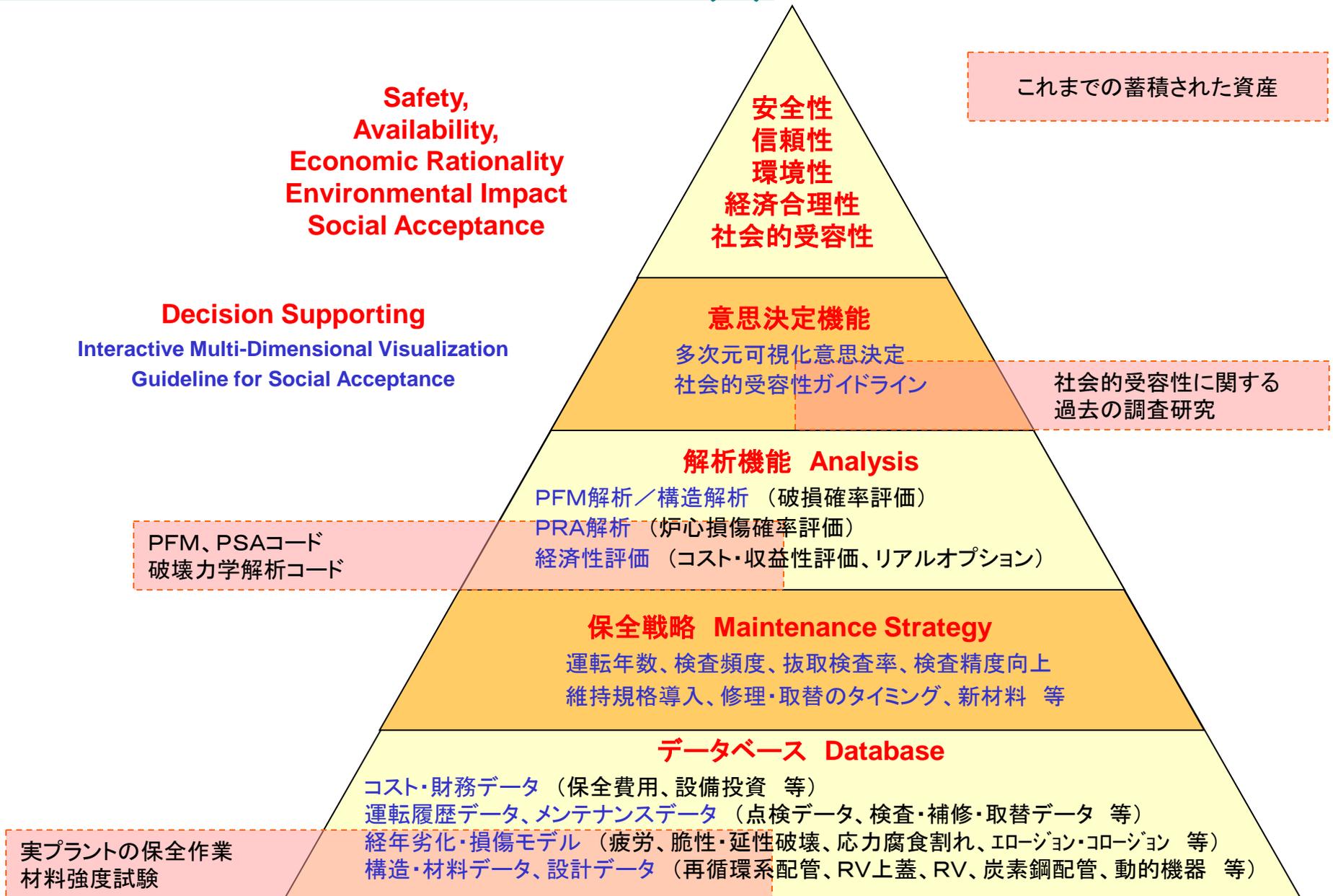
- Dr. Mainte is a PFM-based decision-making simulator to optimize maintenance strategies such as
ex. operation years, inspection interval, crack detectability, crack sizing accuracy, sampling inspection, repair or replace, timing of replacement, various maintenance rules
of typical components and piping systems in nuclear power plants totally and quantitatively in terms of
 - (1) **Safety** (core damage)
 - (2) **Availability** (unexpected shutdown)
 - (3) **Economic rationality** (both from cost and profit)
 - (4) **Environmental impact** (CO2 release)
 - (5) **Social acceptance** (social cost).
- Interactive “**Divided Multi-Dimensional Visualization Method**” and “**Neural network technique**” are used to optimize maintenance strategies efficiently.

リスク／ベネフィット解析により「社会的説明責任」「合意形成」にも寄与

Outline of Dr. Mainte (1)



Outline of Dr. Mainte (2)



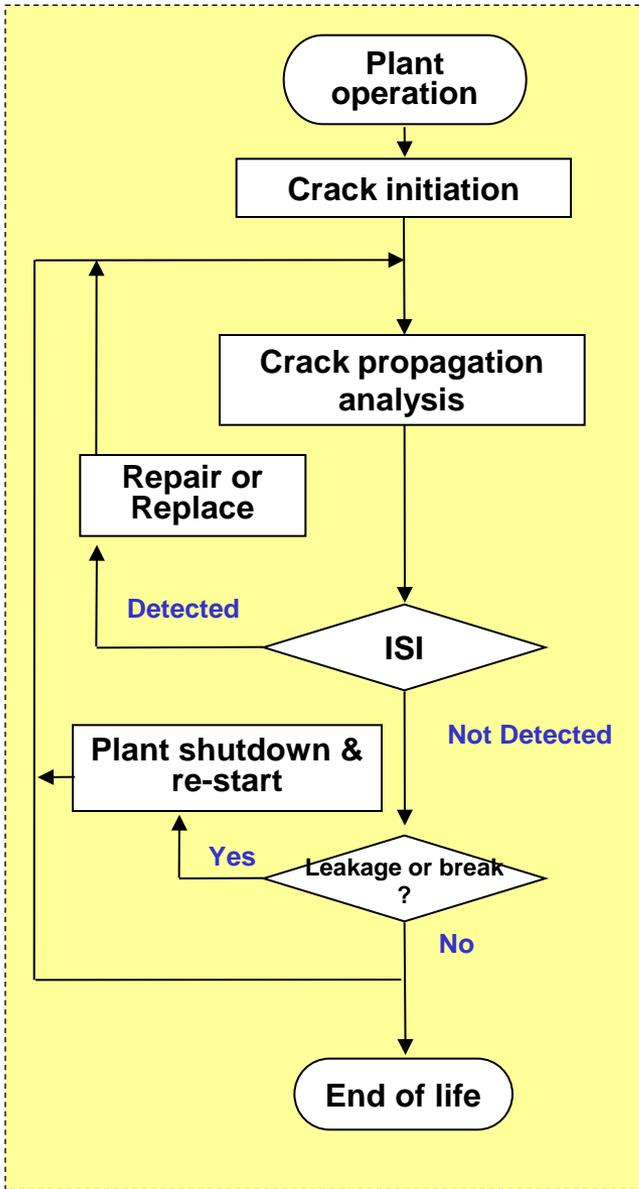
Outline of Dr. Mainte (3)

Components & Piping systems		Degradation Mechanism	Reliability Analysis	Safety Analysis & Social Acceptance	Economic & Environmental Analyses
PWR *1	SG tubes	PWSCC*2	<ul style="list-style-type: none"> ● PFM engines <ul style="list-style-type: none"> ① Modified pc-PRAISE ② PASCAL [JAEA] ③ SANTA [NFI] ● Stress analysis engine ADVENTURE [U of Tokyo & AE] (Applicable to complex geometries)	<ul style="list-style-type: none"> ● Safety Analysis Apply PFM analysis results to PRA <ul style="list-style-type: none"> ● Social Acceptance Supply a guideline for social acceptance of risk-based maintenance	<ul style="list-style-type: none"> ● Cost Analysis (Just cost) <ul style="list-style-type: none"> ● Profitability Analysis (NPV) <ul style="list-style-type: none"> ● Real Option Analysis (RO) <ul style="list-style-type: none"> ● CO₂ release Comparison with alternative power generation
	RV head nozzles	SCC*4			
	PL piping	Fatigue			
BWR *5	PLR piping	SCC			
PWR & BWR	RV*3	PTS*6			
	Carbon steel pipes	Erosion & Corrosion			
	Dynamic components	Wear, Erosion, etc.			

*1 Pressurized Water Reactor *2 Primary Water Stress Corrosion Cracking *3 Reactor Vessel

*4 Stress Corrosion Cracking *5 Boiling Water Reactor *6 Pressurized Thermal Shock

Example of PFM analysis flow



EXAMPLES OF PFM ANALYSES PARAMETERS

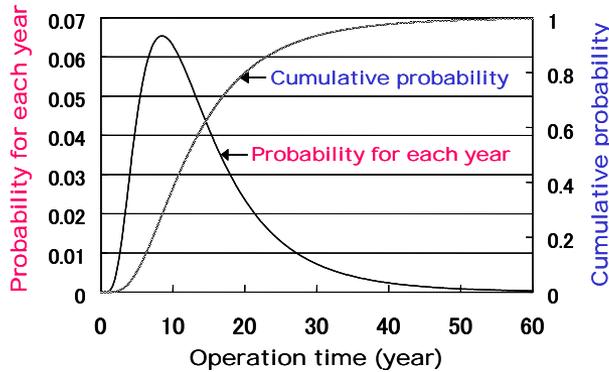


Fig. Crack initiation probability

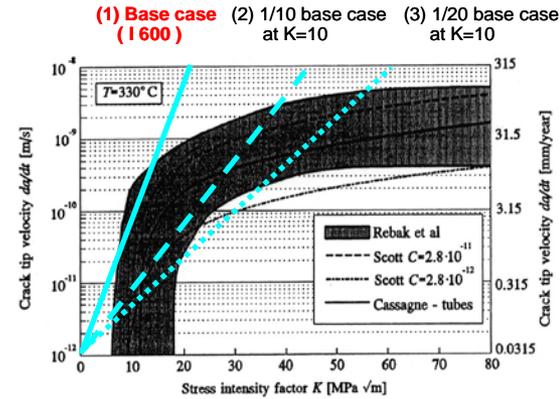


Fig. Crack propagation laws

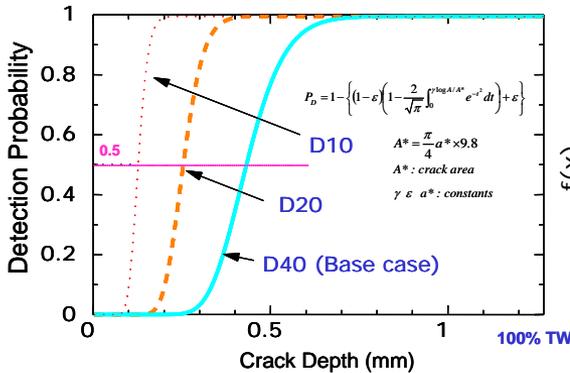


Fig. NDT detection probability

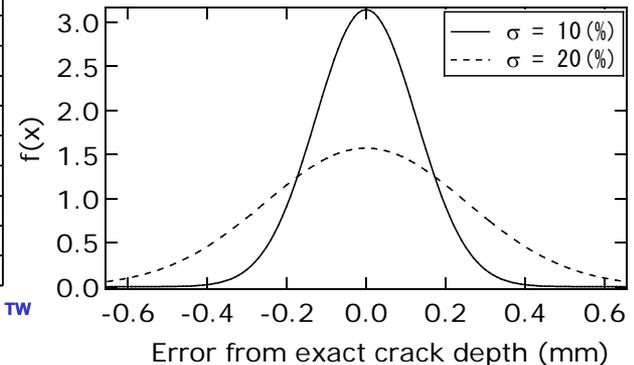
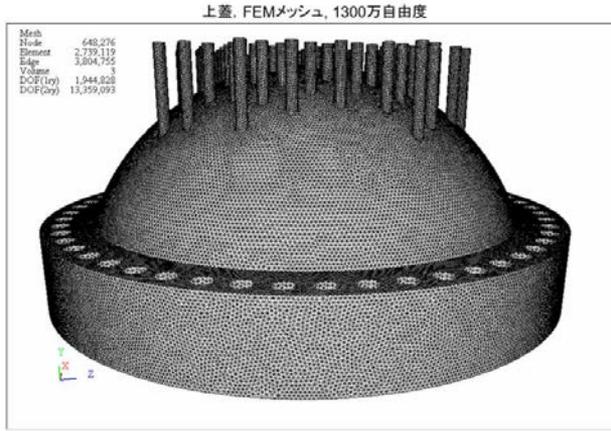


Fig. NDT sizing error

Ex. of Stress analysis - RV head nozzle of PWR -



Computational Mechanics System for Large Scale Analysis and Design
ADVENTURE (ADVanced ENgineering analysis Tool for ULtra large REal world)
 10 to 100 million DOF meshes using various parallel and distributed computer
 (1 million DOF is maximum in conventional analyses.)

Fig. 13 million DOF meshes of PWR RV head.

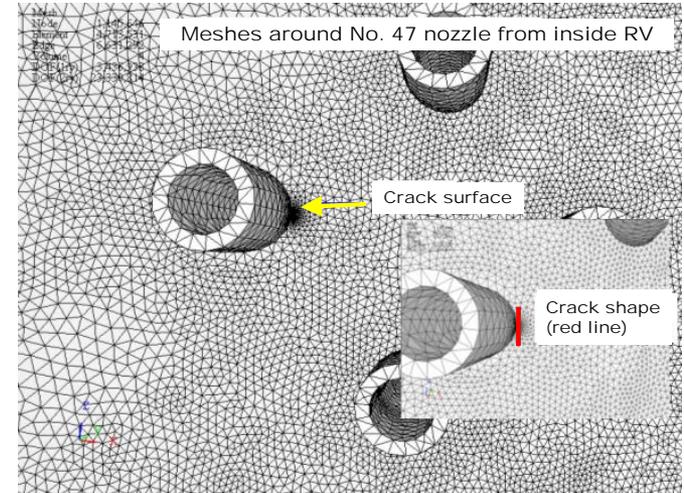


Fig. Calculation of stress intensity factors of cracks existed in the complex shape components.

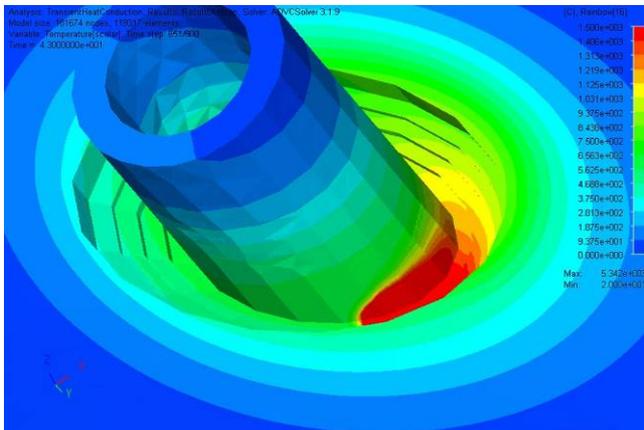


Fig. Residual stress analysis during welding process.

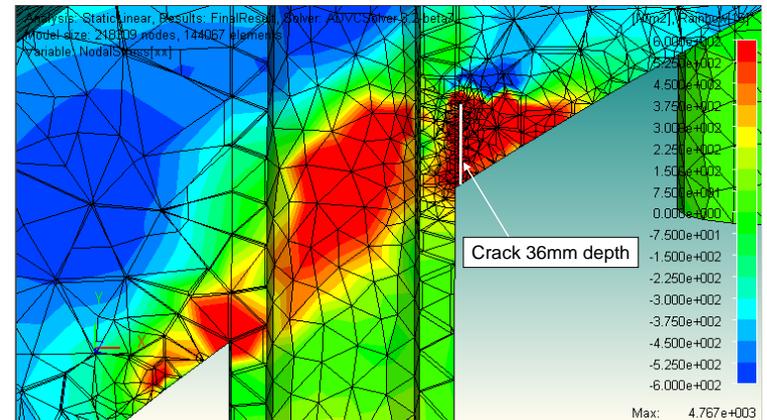


Fig. Residual stress distribution after welding.

Ex. of PFM analysis - RV head nozzle of PWR -

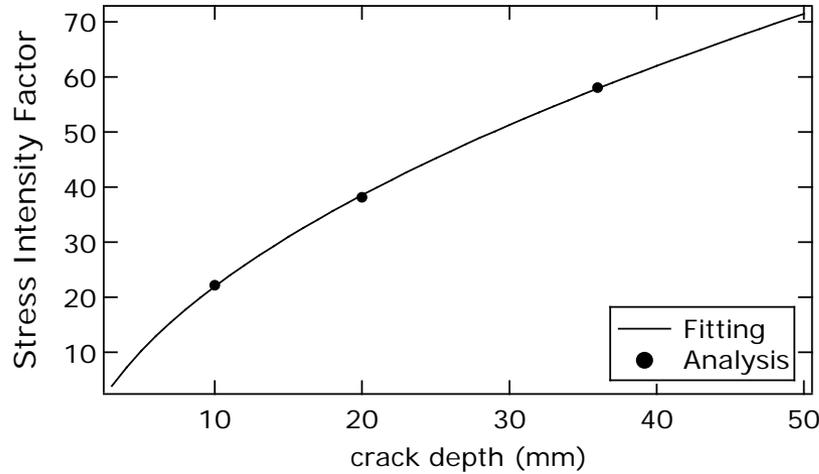


図 き裂深さに対するき裂先端の応力拡大係数(変位外挿法)

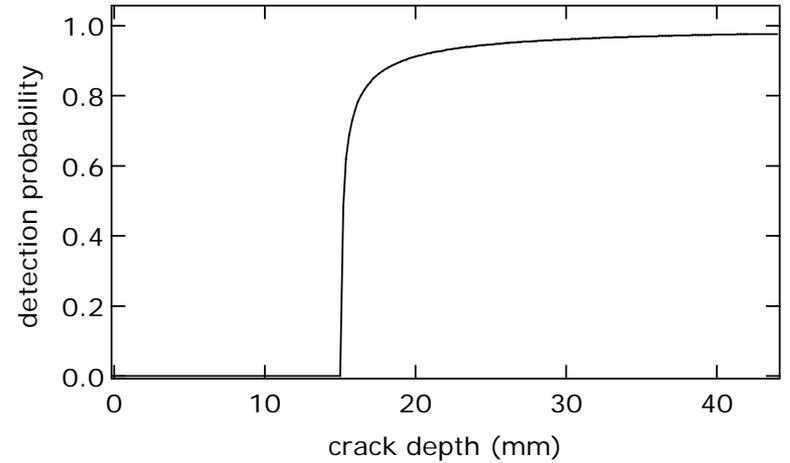


図 本解析に用いたき裂深さに対するき裂検出確率
注: き裂深さ(及び見逃し確率0.5%)に従ってき裂が検出され、補修されるものとした。

残留応力考慮あり			
き裂形状 (長さ×深さ) [mm]	き裂先端 [MPa√m]	開口部 (0° 方向) [MPa√m]	開口部 (180° 方向) [MPa√m]
5×10	22.2	56.1	60.4
10×20	38.2	122.0	125.6
18×36	58.1	159.8	172.3

残留応力考慮なし			
き裂形状 (長さ×深さ) [mm]	き裂先端 [MPa√m]	開口部 (0° 方向) [MPa√m]	開口部 (180° 方向) [MPa√m]
10×20	1.7	16.2	16.0
18×36	2.2	19.4	20.0

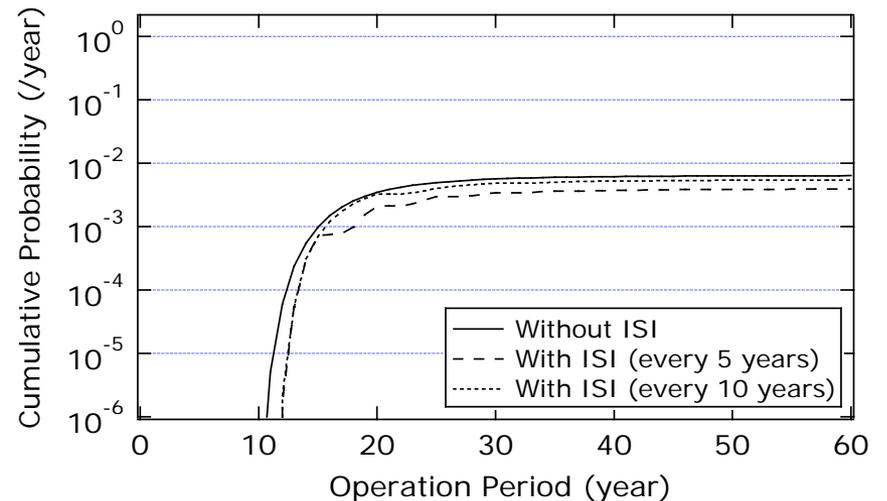


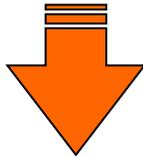
図 解析例 PWR上部蓋管台溶接部における漏洩確率

■ Application to Safety evaluation (1)

Effect of ISI conditions for simplified PWR primary cooling piping systems on CDF.

■ PFM analysis

- PFM analysis
- Break probability per welding line
- Break probability per segment
- Break probability per system



■ PRA

- CCDP (Conditional Core Damage Probability)
- CDF (Core Damage Frequency)

Application to Safety evaluation (2)

Effect of ISI conditions for simplified PWR primary cooling piping systems on CDF.

Simplified PWR primary cooling piping

Piping	Initiating events	OD (mm)	Thickness (mm)	Welding line
Small diameter	Small break LOCA	21.7	4.7	100
Medium diameter	Medium break LOCA	60.5	8.7	100
Large diameter	Large break LOCA	216.3	23.0	100

PFM analysis conditions :

配管材料		SUS316 相当材
製造欠陥存在確率		Moodの理論, Hahnの式, Harrisのデータに基づく
製造欠陥の大きさ分布		Marshallの指数関数分布, Abramowitzの式に基づく
PSIおよび検査品質		RT実施, UT実施, UT検査品質はやや悪い(Marginal)
過渡事象	起動停止	冷却材温度; 288°C. 応力; 21kgf/mm ² . 頻度; 2回/年
	一様応力	応力; 21kgf/mm ² . 頻度; 10回/年
	熱衝撃	温度変化; 149°C(ステップ状). 頻度; 10回/年
ISIの実施程度		検査しない
き裂進展速度		Harrisの式に基づく
漏えい検知能力		1gpm (gallon per minute)

Application to Safety evaluation (3)

Effect of ISI conditions for simplified PWR primary cooling piping systems on CDF.

PFM analysis results :

Initiating events	Break probability per crack	Break probability per welding line	Initiating events frequency (/ reactor year)
Small break LOCA	3.0×10^{-5}	3.1×10^{-10}	7.7×10^{-10}
Medium break LOCA	4.1×10^{-9}	5.1×10^{-13}	1.3×10^{-12}
Large break LOCA	1.7×10^{-13}	5.9×10^{-16}	1.5×10^{-15}

PRA results : Examples of conditional CDP

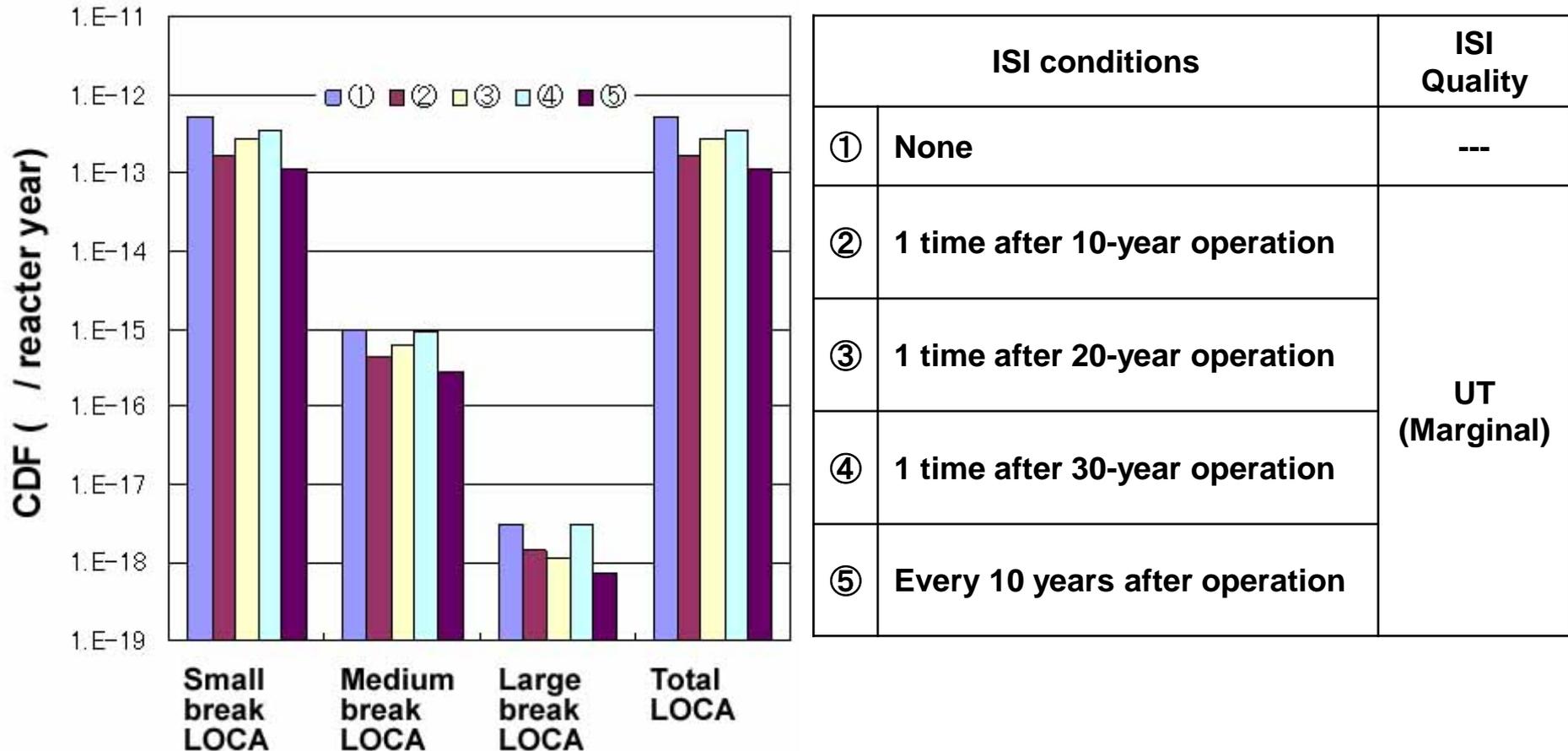
Initiating events	Conditional CDP
Small break LOCA	6.8×10^{-4}
Medium break LOCA	7.7×10^{-4}
Large break LOCA	2.1×10^{-3}

Safety evaluation results : CDF due to initiating events

Initiating events	CDF (/ reactor year)
Small break LOCA	5.2×10^{-13}
Medium break LOCA	9.9×10^{-16}
Large break LOCA	3.1×10^{-18}

Application to Safety evaluation (4)

Effect of ISI conditions for simplified PWR primary cooling piping systems on CDF.



■ Application to Economic evaluation (1)

Analysis for the effect of maintenance strategies in terms of costs and profitability.

- Cost analysis :

Considering only costs.

- Profitability analysis * : financial method using NPV :

Considering both costs and profits.

* **Note : Risk-based or cost-based analyses can not tell whether or not electricity generation business will pay. Thus, profitability must be analyzed.**

- Real Option analysis : up-to-date financial method :

Considering economic values of the flexibility of strategies quantitatively.

ex. Decision making based on upcoming information

Application to Economic evaluation (2)

Profitability analysis : NPV (Net Present Value)

Power generation Cost
(except SG maintenance cost)

$$NPV(T) = \sum_{t=1}^T \frac{S(t) - C_{\text{others}}(t) - C_{\text{R\&D}}(t) - C_{\text{ins.}}(t) - \frac{N_{\text{tube}} C_{\text{repair}} p_{\text{repair}}(t)}{(1+r_b)^t} - C_{\text{leak}} p_{\text{leak}}(t) - C_{\text{rupture}} p_{\text{rupture}}(t)}{(1+r_b)^t} \times (1-r_{\text{tax}})$$

Discount Tax

● Numerator :
Revenue minus various costs

● Denominator :
Discount rate

If $NPV > 0$, it is justified to be worth while investing.

Application to Economic evaluation : SG tubes

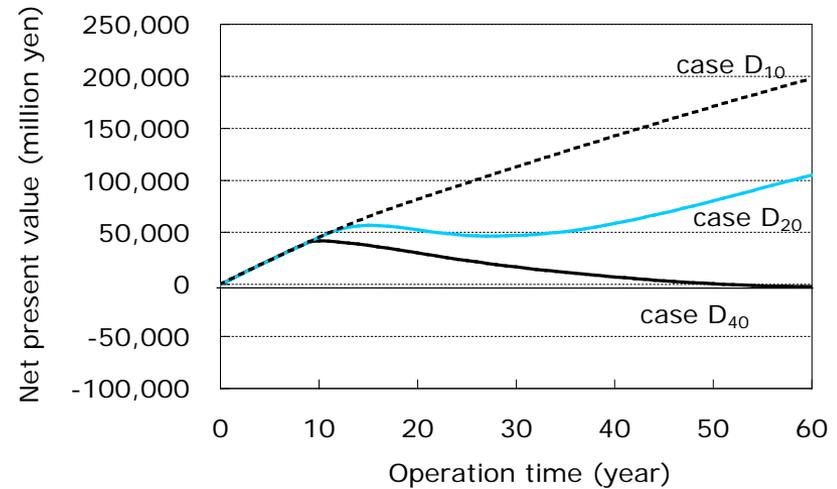
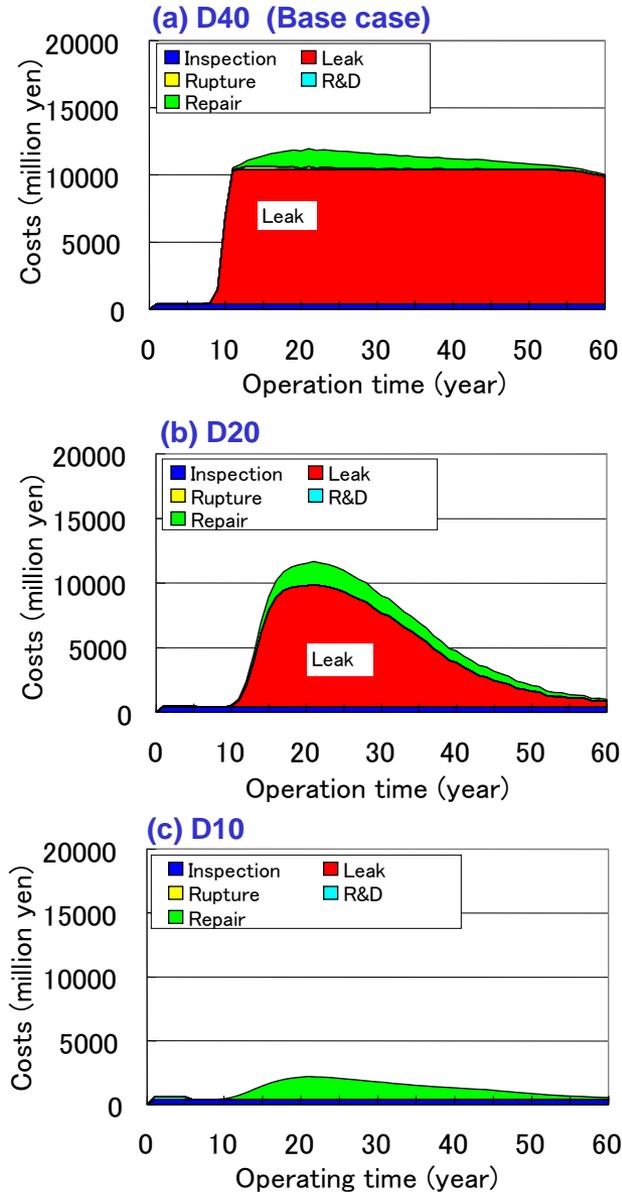


Figure NPV for various NDE detectability.

Inconel 600 case

Figure Annual costs for various NDE detectability.

■ Application to Economic evaluation : Real Option

Real Option analysis

Cost analysis and Profitability analysis on maintenance strategies



If we know what will happen in the future, then we may just calculate and compare the costs and NPV of maintenance scenarios. However, nobody knows what will happen in the future. Therefore, it should be useful to evaluate economic values of flexible decision makings over the uncertainties in the future.



Real option analysis

It can evaluate quantitatively the economic values (cash) of the effect of flexible decision makings over the uncertainties in the future.

Ex. : Economic value of decision makings based on upcoming information.

Application to Economic evaluation : Real Option

BWR PLR piping

Real Option Analysis conditions:

Evaluate the economic value of having an option of applying a new inspection system anytime during 11-13 operational years to PLR piping system (316NG, 400A) which has 10 welding lines.

Conventional inspection:

50% detectability of 50%TW cracks

New inspection:

50% detectability of 25%TW cracks

but with 200% cost.

Table Tentative values used in the real option analysis on Maintenance activities of PLR lines.

Annual sales per unit (M yen)	80,000
Cost for power generation (M yen) (except PLR maintenance cost)	70,000
Inspection cost / weld (M yen)	5
New inspection cost / weld (M yen)	10
Repair cost / weld (M yen)	40
Replacement cost / weld (M yen)	70
Expected loss from leakage (M yen)	120,000
Risk free rate	0.01
NPV of future expected cash flow = Original asset value = S_0 (M yen)	23,961
Volatility = σ	0.0504
Option period = T (year)	3
Step number	3
Step period = Option period / Step number = δt	1
Up rate = $u = e^{\sigma\sqrt{\delta t}}$	1.0517
Down rate = $d = e^{-\sigma\sqrt{\delta t}}$	0.9508
Risk neutral probability = $p = (e^{rf*\delta t} - d) / (u - d)$	0.5870

Application to Economic evaluation : Real Option

BWR PLR piping

(A): 従来の検査技術を継続する場合

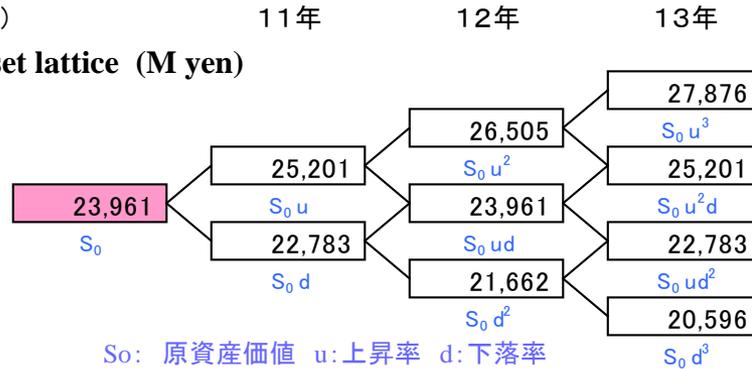
(A): Just keeping conventional inspection

原資産格子 (百万円)

(ステップ1)

Original asset lattice (M yen)

(Step 1)



(B): 新検査技術を導入するオプションを持つ場合

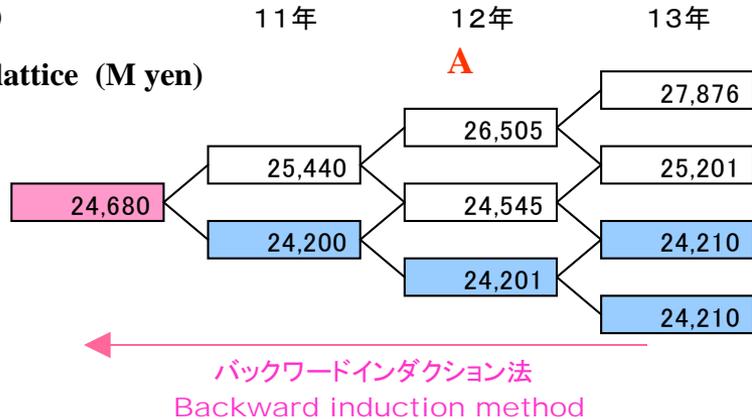
(B): Having an option of new inspection

評価格子 (百万円)

(ステップ2)

Evaluation lattice (M yen)

(Step 2)



オプション価値: 7億1900万円
Option value: approx. 7 M US\$

解説 リアルオプション評価に2項格子モデルを採用

(A)は運開後11-13年目における原資産格子(将来の期待キャッシュフローの現在価値の変動)

(B)は(A)の各格子点において、新検査技術を導入した方が利益が最大化されるかを評価した評価格子
ブルーの格子点が新検査技術を導入した場合である。

(B)の評価格子に対してオプション期限である運開後13年目より、バックワードインダクション法*によってオプション開始点(ピンクの格子点)である運開後11年目当初までさかのぼって、オプションを持つ場合の将来の期待キャッシュフローを再計算

(B)と(A)の先頭のピンクの格子点の差をとることによって、11-13年の3年間に新検査技術を導入するオプションを持つ場合の価値が求まり、約7億1900万円となる。

バックワードインダクション法*

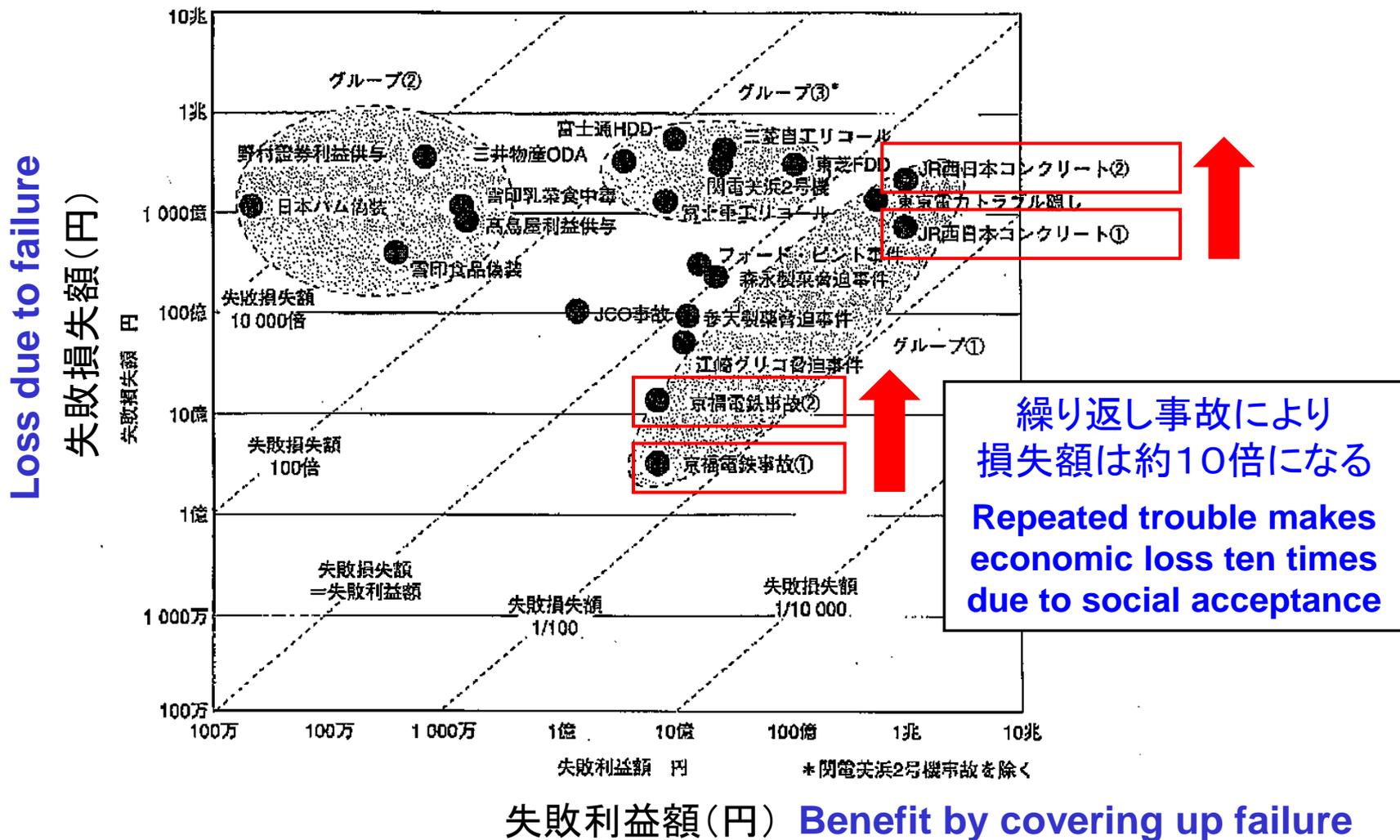
リスク中立確率 $p = (e^{rf \cdot \Delta t} - d) / (u - d)$ を用いて、例えば評価格子点 A であれば、Aから分岐する2つの13年目の格子点の数値を用いて

$$[p(27876) + (1 - p)(25201)] \exp^{-rf \cdot \Delta t}$$

によって計算する。

Application to Social acceptance (1)

失敗利益額と失敗損失額の算出結果*



*寺邊 正大、他：失敗の利益と損失, 日本機械学会誌, Vol.106, No.1020 (2003)

Application to Social acceptance (2)

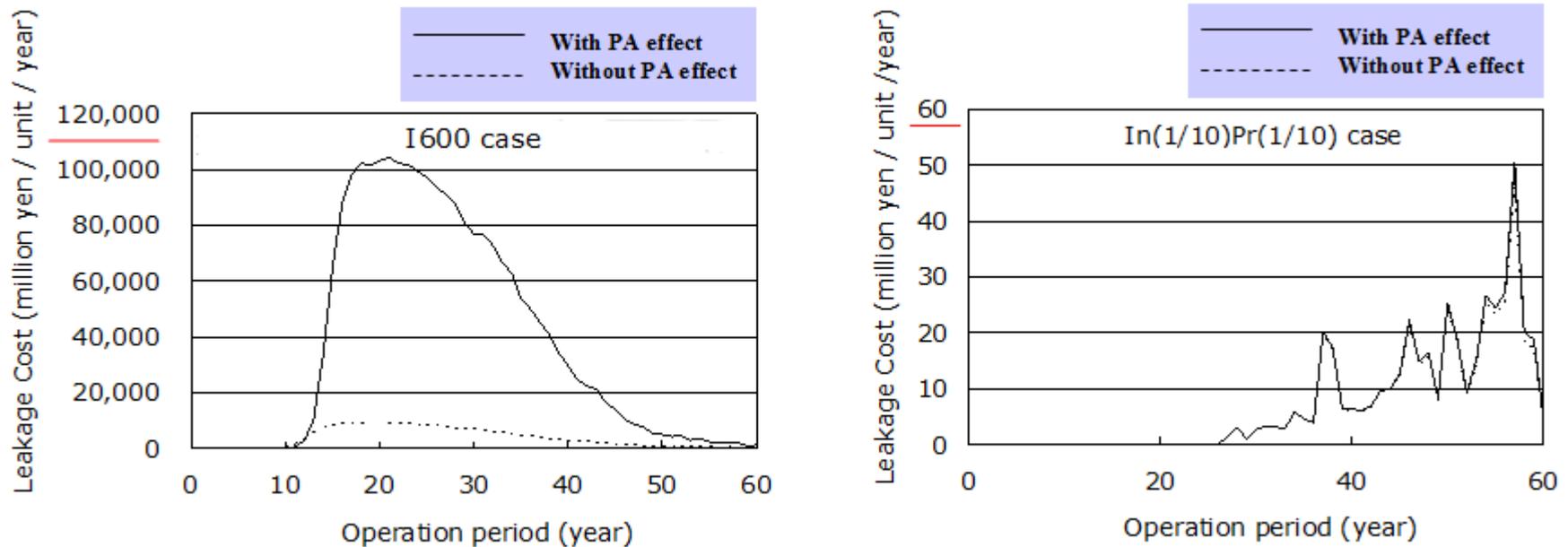


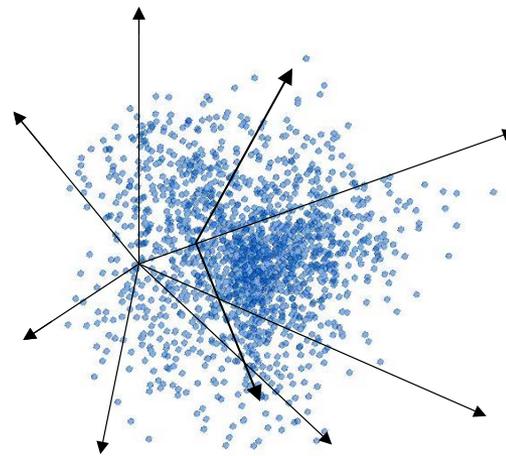
Fig. Economic evaluation model including maintenance effect on PA cost in terms of the frequency of leakage accidents.

Assumption : In case an additional leakage happens within 3 years, the leakage cost becomes 10 times larger than the ordinary leakage cost.

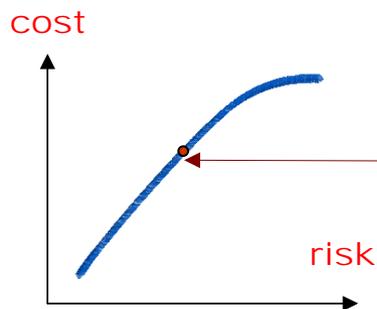
■ Maintenance optimization through Dr. Mainte (1)

Interactive “Divided Multi-Dimensional Visualization Method”
Optimum solution of multi-objective problems

Image of 9-dimensional space

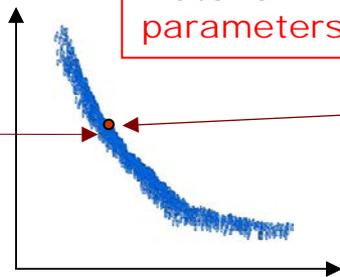


Criteria of decision making



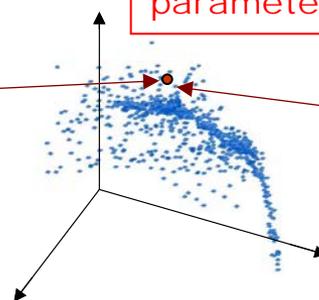
2-dimensional
objective function space

Material
parameters



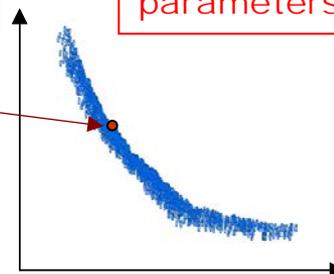
Partial space of
2-dimensional
designing variables

Inspection
parameters



Partial space of
3-dimensional
designing variables

Regulatory
parameters



Partial space of
2-dimensional
designing variables

【目的関数空間】

【設計変数空間】

【設計変数空間】

【設計変数空間】

■ Maintenance optimization through Dr. Mainte (2)

Item	Conditions
Target component	BWR PLR piping system (400A)
Degradation mode	SCC of welding joints
Material	SUS316 (Residual stress is considered)
Numbers of joint	20
Maintenance strategy (Design parameters)	<ul style="list-style-type: none"> ▪ Inspection interval : 100% / 3, 5, 7 10, 13 years ▪ Improving crack detectability by R&D : Crack depth of 50% detectable are (1) 3.2mm (2) 1.5mm (3) 0.8mm. 400 and 1000 Myen budgets for (2) and (3), respectively. ▪ Maintenance when cracks are detected : repair or replace
Objective functions	<ul style="list-style-type: none"> ▪ Probability of pipe rupture ▪ Probability of pipe leakage ▪ CO2 release volume ▪ NPV (Net Present Value), etc
Constraint conditions	<ul style="list-style-type: none"> ▪ Accumulative probability of pipe rupture $\leq 10^{-4}$ ▪ Accumulative NPV ≥ 100 billion yen

Maintenance optimization through Dr. Mainte (3)

Table Conditions of PFM analyses

Analysis code	Dr. Mainte
Pipe material	SUS316 NG
Pipe diameter	400A: 8 inch (406.4 mm)
Pie thickness	400A: 0.84 inch (21.3 mm)
Operation period	60 years
Operation temperature	288 °C
Operation pressure	87.5 atm
Flow stress	31.6kg/mm2 (mean) 1.3 kg/mm2 (standard deviation)
Residual stress due to welding	Residual stress of medium diameter pipes
Crack initiation Probability	<p>mean value of $t_{1\sigma} = -7.72 - 5.39 \log(D_\sigma)$ std. dev. of $t_{1\sigma} = 0.3081$</p> <p>$D_\sigma = f_1(\text{material})f_2(\text{environment})f_3(\text{loading})$</p> <p>$f_1 = 1.879$</p> <p>$f_2 = O_2^{0.24} \exp\left[\frac{-1123}{T+273}\right] \log(4.0\gamma^{0.35})$</p> <p>$f_{3\sigma} = (2.21 \times 10^{-15} \sigma^{6.0})^{0.49}$</p> <p>O2: Oxygen conc., γ: Conductivity, σ: Stress, T: Temp.</p>
Crack initiation numbers	400A : 23/welding line
Crack propagation rate	<p>Based on Harris equation $\log \dot{a} = C_1 + C_2(C_3 \log[f_2(\text{env.})]) + C_4 K$</p> <p>C1: 0.8192, C2: 0.03621, C3 (mean) : -4.006, C3 (std.) : 0.5792 C4: 1.19</p>
ISI interval	100 % / 3, 5, 7, 10, 13 years
Maintenance options	Repair or Replace

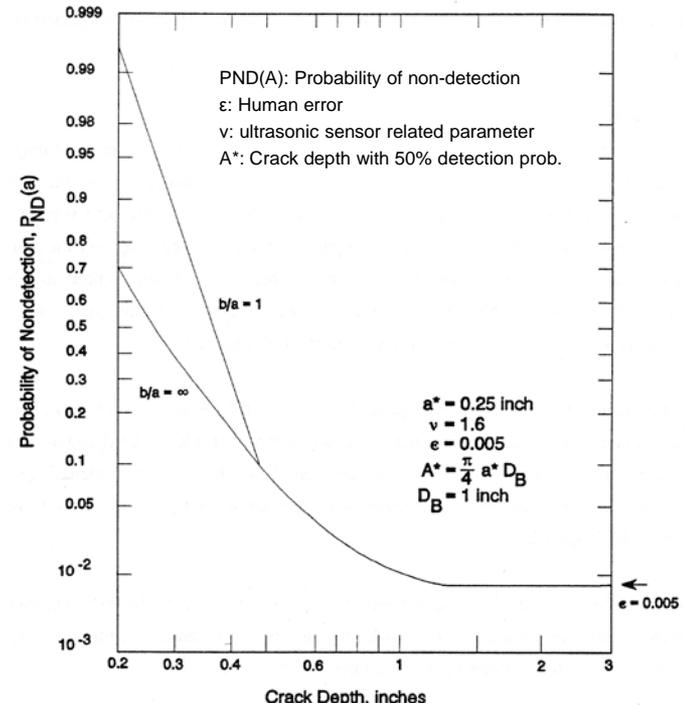


Fig. Probability of non-detection by UT.

■ Maintenance optimization through Dr. Mainte (4)

Table Conditions of economic efficiency evaluations

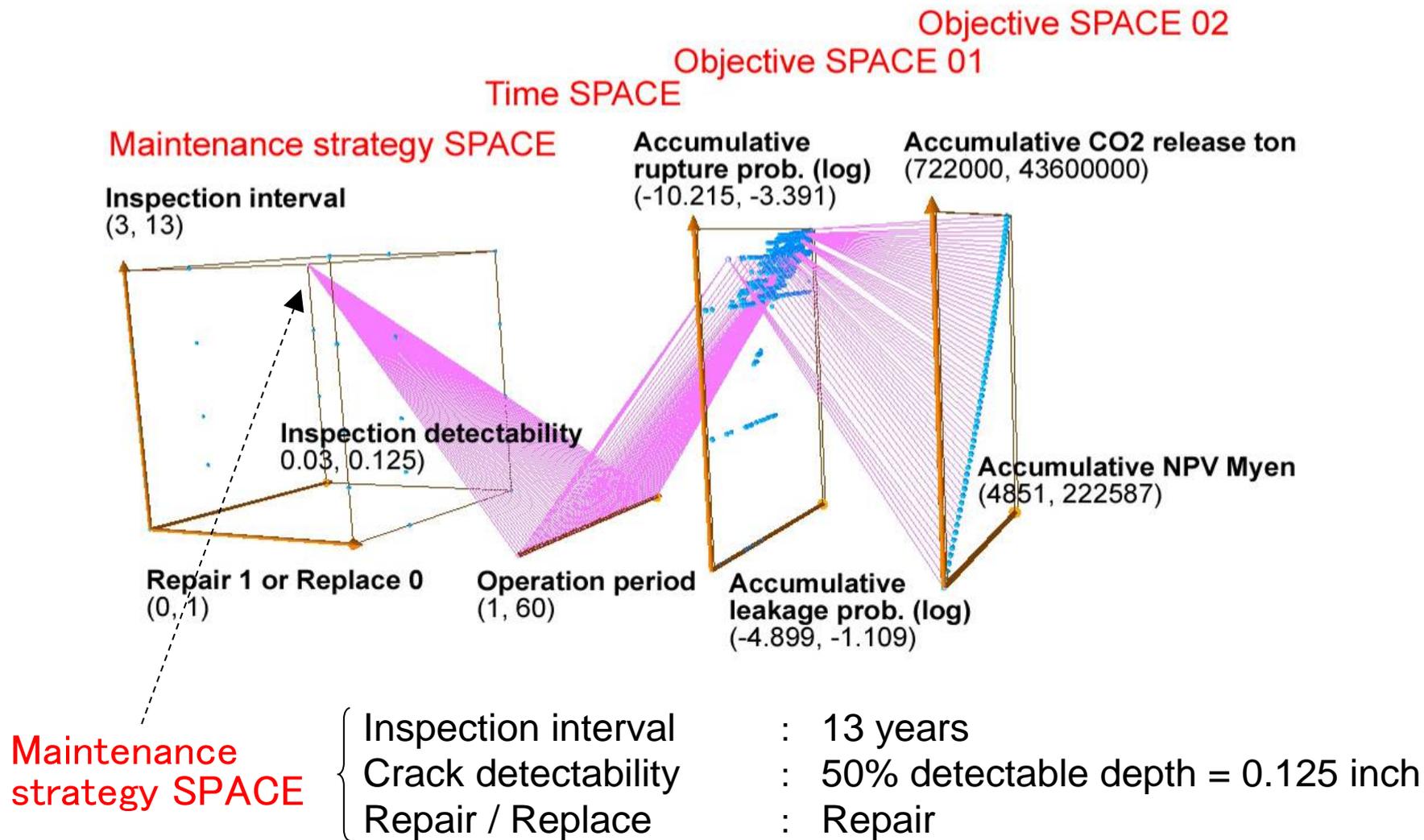
Annual Sales per unit (M yen)	80,000
Sales cost (M yen)	70,000
Inspection cost / weld line (M yen)	5
Repair cost / weld line (M yen)	40
Replacement cost / weld line (M yen)	70
Loss due to Leakage (M yen)	120,000
Risk free rate	0.01

Table Conditions of environmental evaluations

Operation conditions	12 month operation 1 month outage after operation (fossil power generation) 100% inspection / 5 years
Output: nuclear power generation Output: fossil alternative power generation	1000 MW 1000 MW
Fossil alternative power generation	During periods of outage and shutdown due to leakage
Pipe leakage	6 month shutdown
CO2 release due to nuclear (g / kWh) CO2 release due to fossil (g / kWh)	20 760
CO2 release cost (yen / ton)	12,000

Maintenance optimization through Dr. Mainte (5)

Maintenance strategies 30 cases × 60 years = **1800 data points** through PFM calculations



■ Maintenance optimization through Dr. Mainte (6)

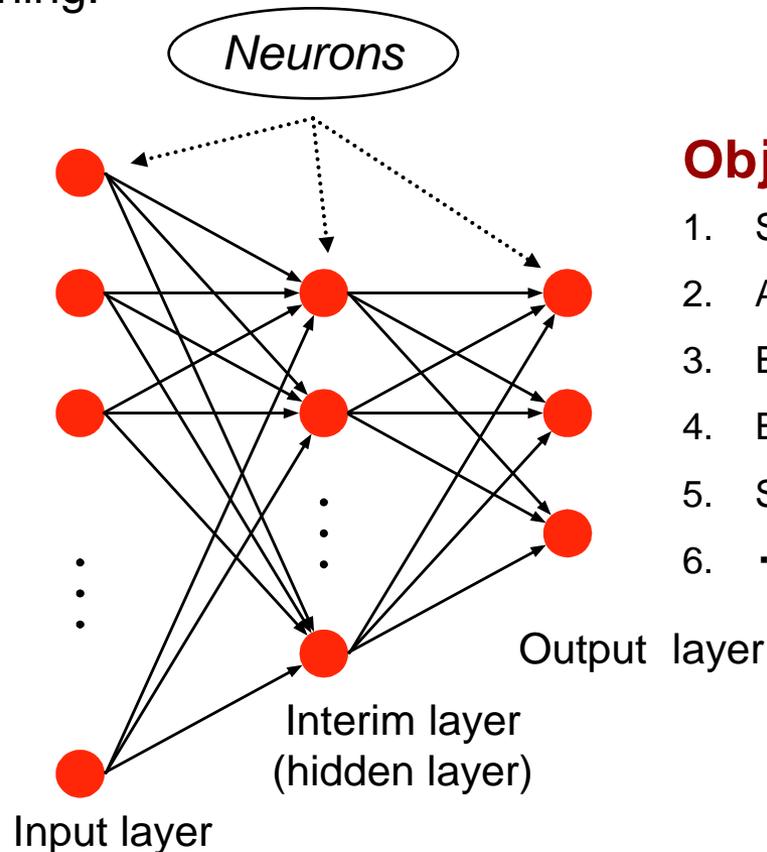
NN Learning of PFM analysis data & Data expansion

What is NN (Neural Network) ?

One type of Artificial Intelligence based on the modeling of complex neural networks of neurons in human brain. Advanced information processing can be realized by repeated learning.

Design Parameters

1. Inspection interval
2. Inspection detectability
3. Repair or Replace
4. JSME code application
5. Long-cycle operation
6. Operation lifetime
7. ...

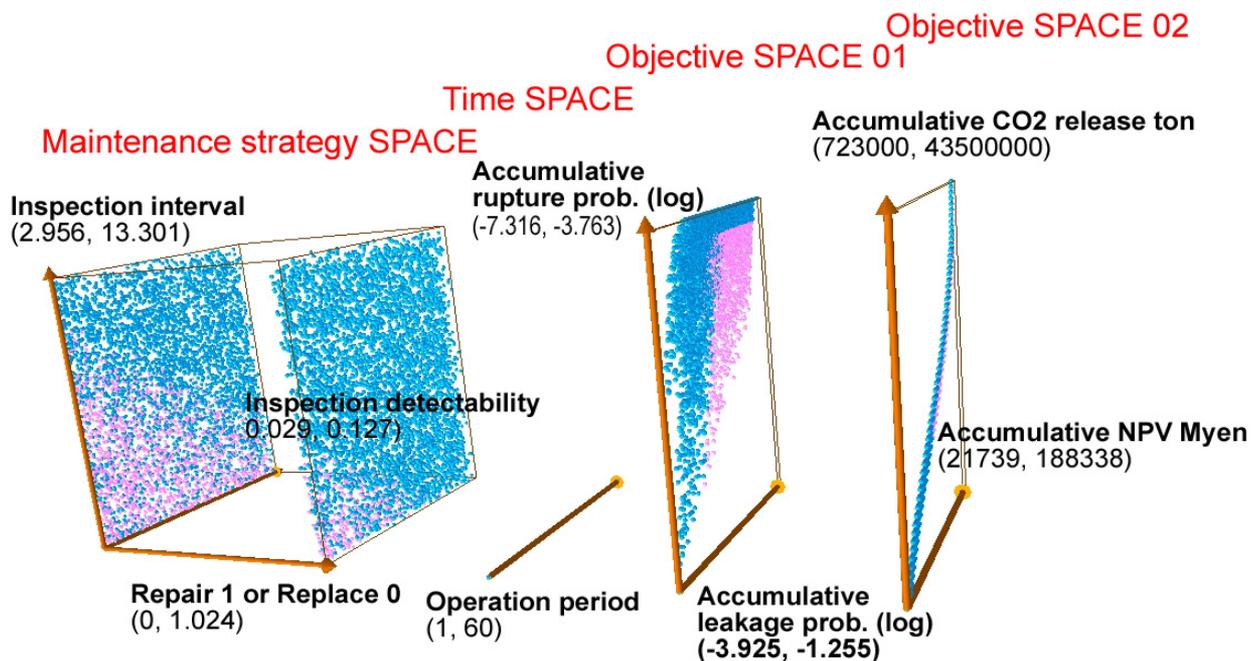


Objective functions

1. Safety
2. Availability
3. Economic efficiency
4. Environmental impact
5. Social acceptance
6. ...

Maintenance optimization through Dr. Mainte (7)

PFM data points expansion from 1800 to 10800 through neural network



Objective SPACE 01 Accumulative rupture $\leq 10^{-4}$

Objective SPACE 02 Accumulative NPV ≥ 100 Billion yen



★ Setting the necessary objective functions in **Objective SPACE** and their constraints values, options of maintenance strategies can be visually shown.

Human Error Reduction through Dr. Mainte (1)

Human error reduction is essential to the further improvement of the reliability of maintenance activities.

Effect of nondetectable probability ϵ (0.0025 - 0.1) independent of the crack depth defined as human error on the leak probability and economic rationality.

超音波検査 非検出確率

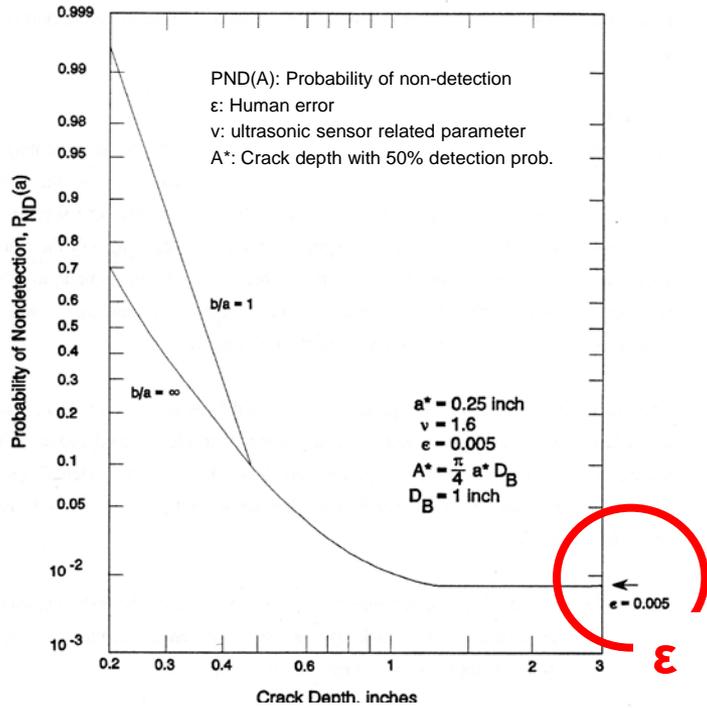
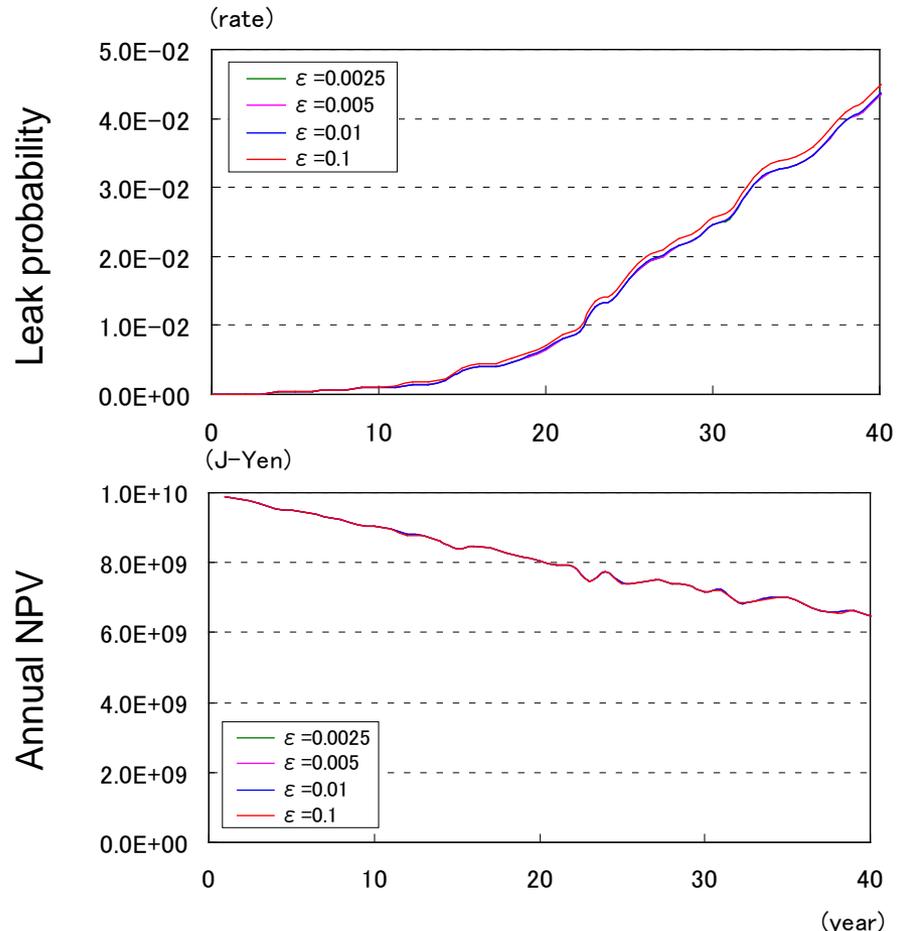


Fig. Probability of non-detection by UT.

き裂深さ



Human Error Reduction through Dr. Maite (2)

ヒューマンエラーは作業環境に大きく依存することが知られている

アンケート調査による「作業環境を改善するためのアプローチ」

Modification of WORKING ENVIRONMENT by questionnaire approach

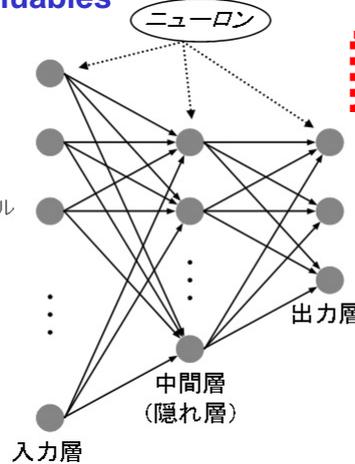
ニューラルネットワーク

NN (Neural Network)

Designing valuables

設計変数

1. 仕事の適性
2. 成長実感
3. 仕事のコントロール
4. 職場環境
5. 活気
6. 意志疎通
7. 上司の接し方
8. 会社の将来性
9. ...



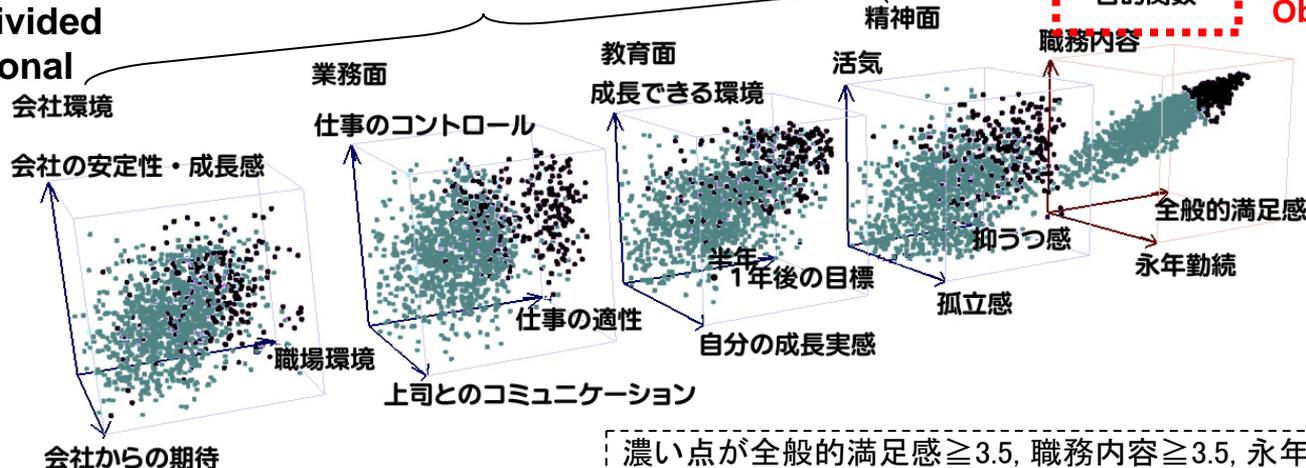
目的関数

Objective functions

1. 仕事の全般的満足感
2. 職務内容の満足感
3. 永年勤続する気持ち

対話型多次元可視化法

Interactive “Divided Multi-Dimensional Visualization Method”



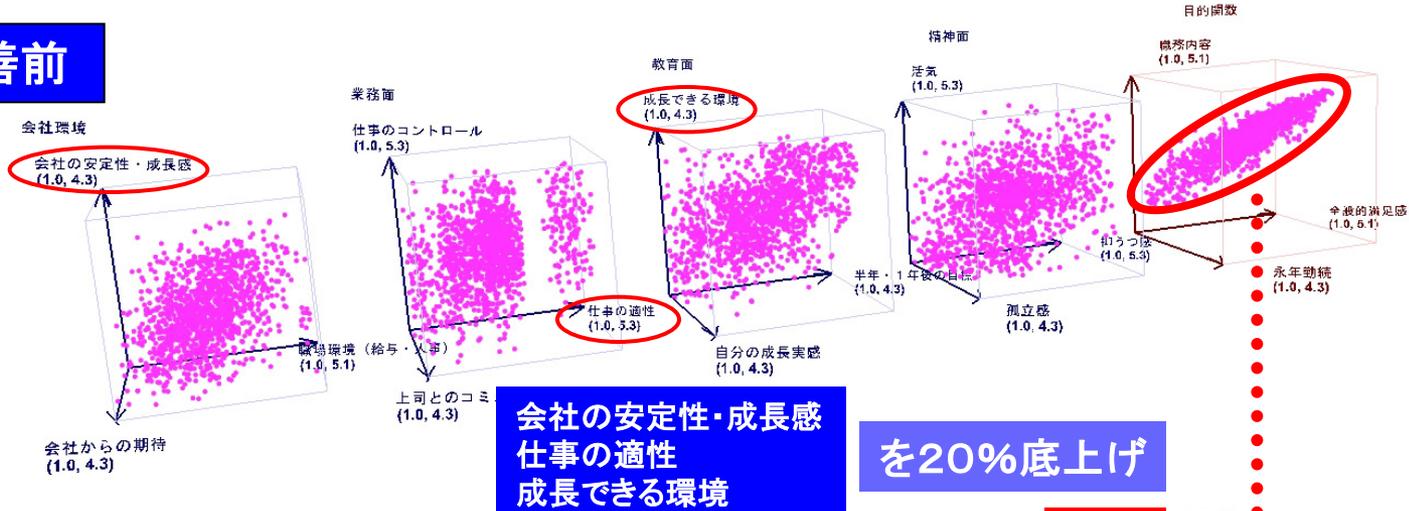
濃い点が全般的満足感 ≥ 3.5 , 職務内容 ≥ 3.5 , 永年勤続 ≥ 2.5 に対応

Human Error Reduction through Dr. Mainte (3)

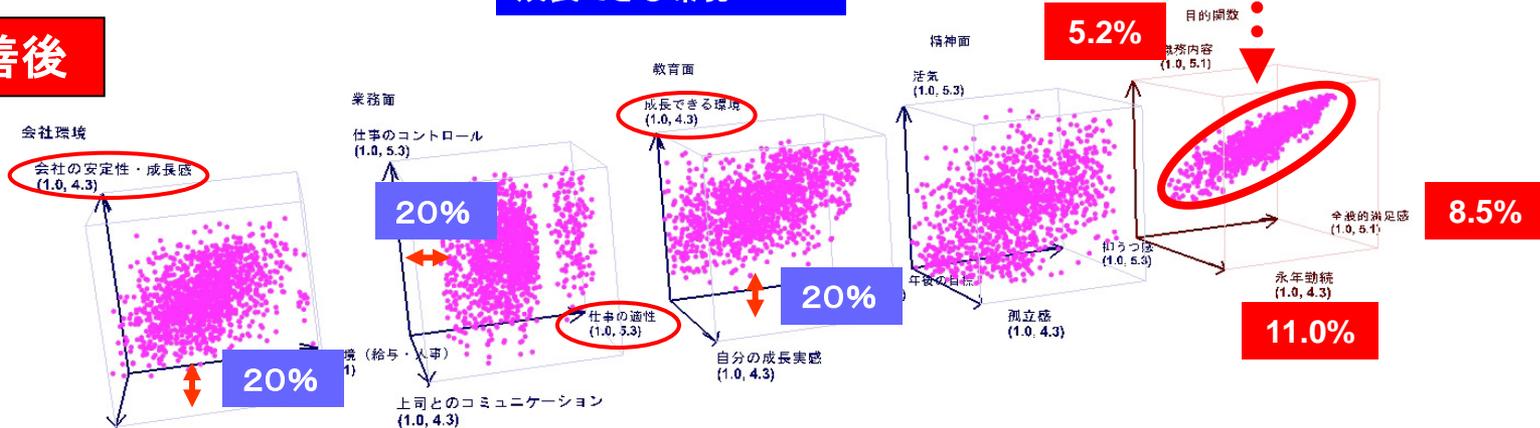
アンケート回答値を修正し、NNで環境改善の効果を予測した例

Quantitative prediction and optimization of improvement effect based on questionnaire.

改善前



改善後

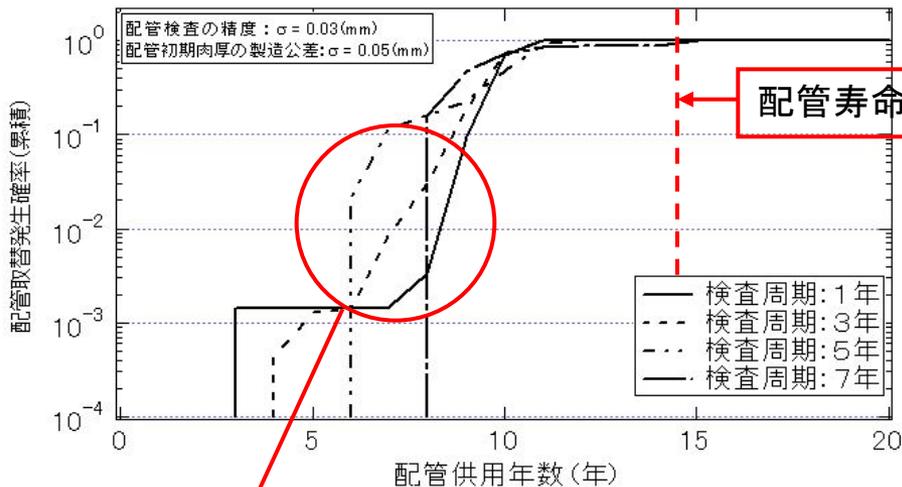


	永年勤続する気持ち	職務内容の満足度	仕事の全般的満足感
改善効果(平均値)	11.0%	5.2%	8.5%

Application to erosion/corrosion of steel piping

解析例：余寿命が5年以上ある時点での 検査周期が及ぼす影響

パラメータ	値
配管	炭素鋼配管(SB42)
配管設計肉厚	10 (mm)
必要肉厚	4.7 (mm)
検査誤差	正規分布、 $\sigma=0.03(\text{mm})$
減肉進展	0.475(mm)/year一定 (実機データを基に仮定)



早期に配管取替が発生

60年運転時点での保全コストの期待値(百万円)*1

検査間隔	1年	3年	5年	7年
検査コスト	180.0	107.2 (- 40.4%)	81.8 (- 54.6%)	57.4 (- 68.1%)
取替コスト	150.4	151.9 (+ 1.0%)	157.2 (+ 4.5%)	158.5 (+ 5.4%)
総計	330.4	259.1 (- 21.6%)	239.0 (- 27.7%)	215.9 (- 37.7%)

*1 検査費用 3.0、取替費用30.0(百万円)で算出

各種確率の評価(配管一本あたり)

検査間隔	1年	3年	5年	7年
破損確率	※	※	※	※
設定必要厚を下回る確率	0.034	0.039	0.127	0.192

※ 解析下限値以下

Application to dynamic components (1)

Introduction of Bayesian estimation method

ベイズ推定： 十分なデータが存在しない場合でも、故障分布関数等を推定する手法の一つ

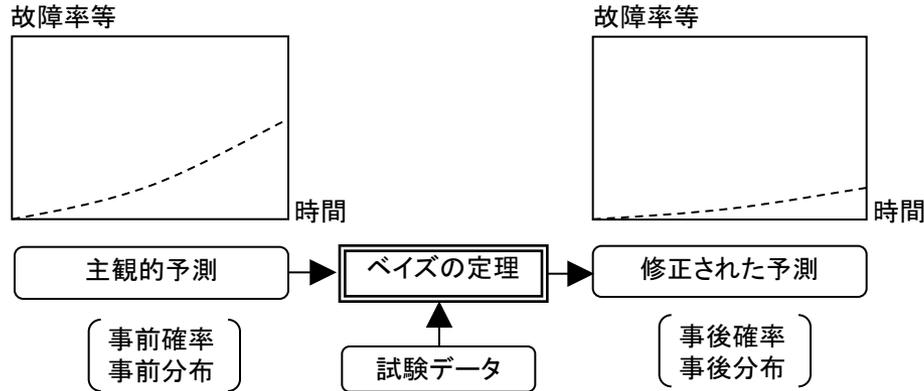


図 ベイズ推定

表 ベイズ推定による寿命密度関数更新の例

ケース	試験サンプル 個数 m(個)	寿命データ T(年)	λ の 期待値
No. 0 (事前分布) $\alpha = 1, \beta = 1$	—	—	0.05
No. 1	10	400	0.033
No. 2	10	500	0.0286
No. 3	10	600	0.025

動的機器の寿命密度関数が指数分布: $\lambda) = \lambda e^{-\lambda t}$ に従うとし、 λ を推定する。

λ の事前分布は次のガンマ分布とする。

$$f(\lambda) = \frac{\beta^\alpha}{\Gamma(\alpha)} \lambda^{\alpha-1} e^{-\beta\lambda}$$

λ の事前分布を $\alpha=1, \beta=1$ として、 m 個のサンプルを試験して、 $T = t_1 + t_2 + \dots + t_m$ なる寿命データを得た。

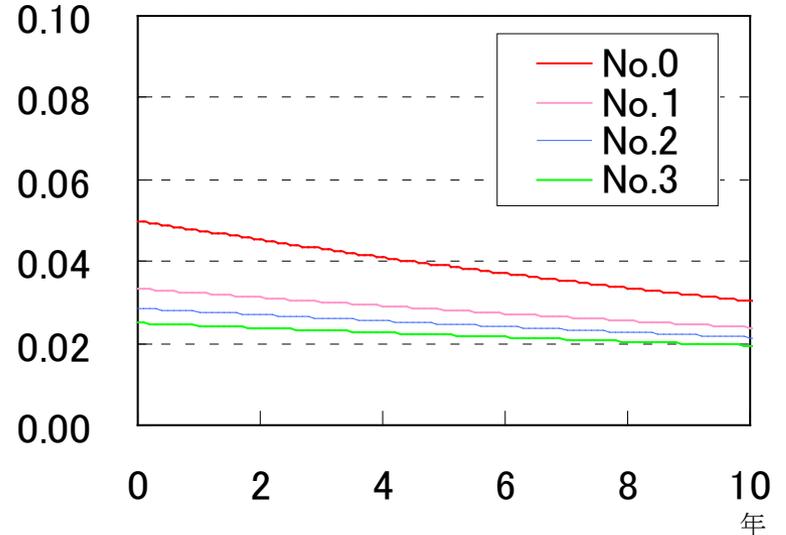


図 動的機器の寿命分布のベイズ推定例

Application to dynamic components (2)

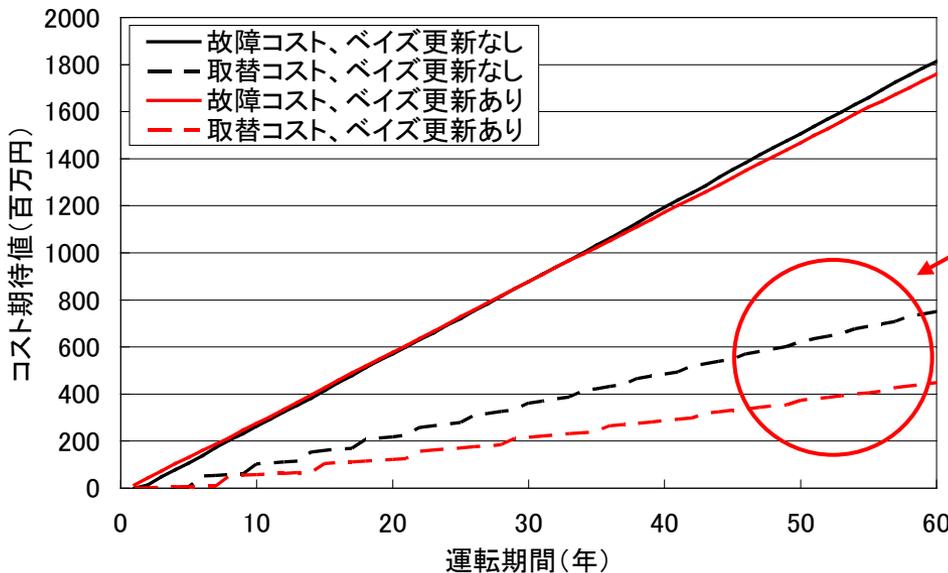
Introduction of Bayesian estimation method

解析例： ベイズ更新による機器取替周期の変更

- 1回目の検査時に、フィールドデータによる寿命密度関数のベイズ更新を実施
- 推定された機器寿命を基に、取替周期を変更

表 ベイズ更新を用いた取替周期の変更

	ベイズ更新	事前分布	事後分布	予定機器寿命 (20%寿命)
ケース1	なし	$\lambda = 0.05$		4.7年
ケース2	あり		$\lambda = 0.286$	7.8年



ベイズ推定による機器取替変更により、運転中のデータからより適切な取替周期へ変更



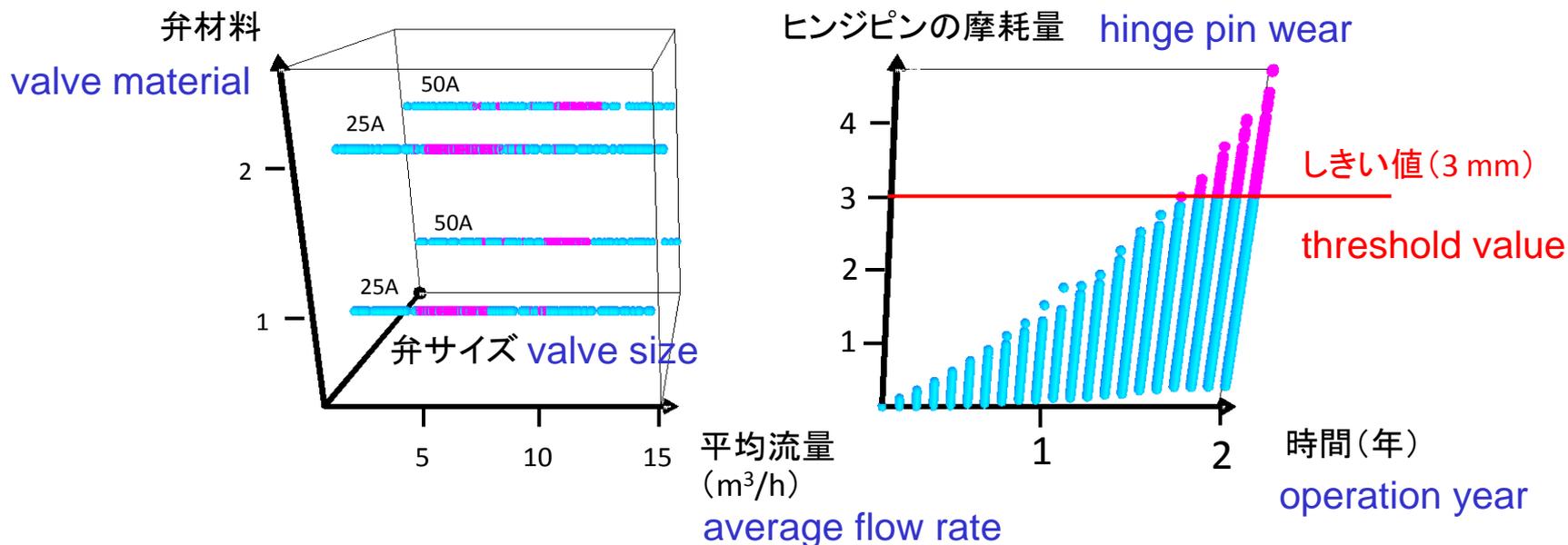
この解析例では
保全コストの低減が期待できる

図 ベイズ更新による故障時の損害及び取替コストの期待値の解析例

Application to check valves

海水ポンプ潤滑水ライン逆止弁への適用

Check valves for seawater pump lubricating water line



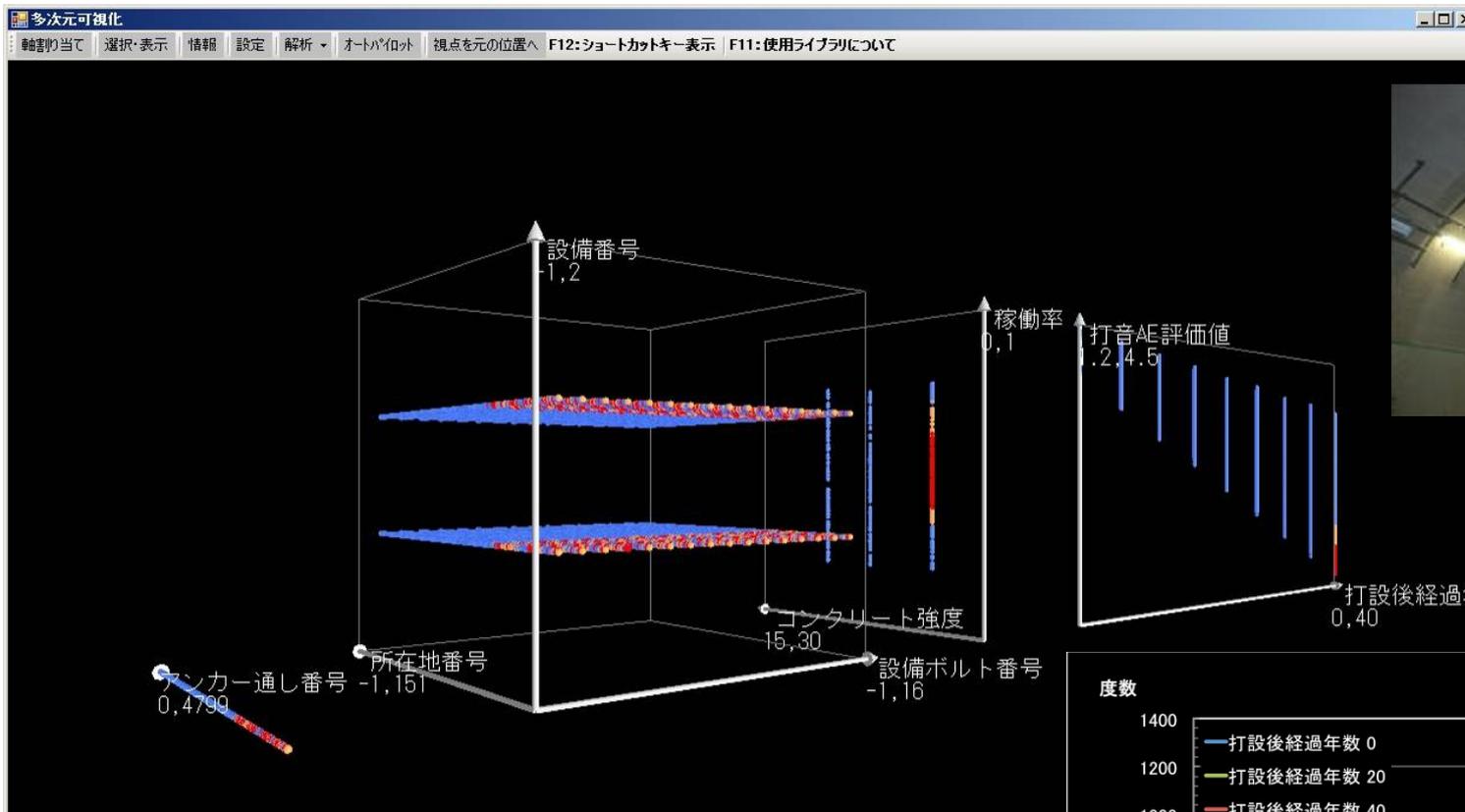
しきい摩耗量を超えている弁に関しては、平均流量をみると、

- ・25Aの弁で材料1については、4-5 m³/h
- ・25Aの弁で材料2については、5-6 m³/h
- ・50Aの弁で材料1については、8-9 m³/h
- ・50Aの弁で材料2については、9-10 m³/h

の範囲集中していることがわかる。

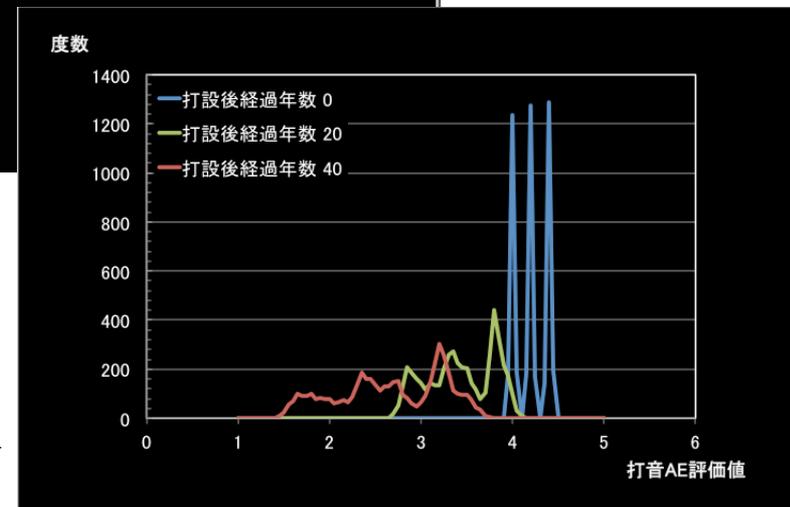
Application to jet fan anchor bolts in tunnels

ジェットファンを固定するアンカーを打音検査で5年ごとに点検し、固有振動値をモニタリングする例



選択点(赤): 打設後経過年40年において打音AE評価値が1.6~1.8
選択点(橙): 打設後経過年40年において打音AE評価値が1.8~2.0
赤くなっている点は、コンクリート強度が弱く(18N/mm²)、且つ
ジェットファン稼働率が40 - 60%のボルトに集中している。

初期状態ではコンクリート強度によって3つのピークがある
打設後の経過によって打音AE評価値が低くなり、分布が広がっていく



■ Guideline of Risk-based Maintenance

Social acceptance based on Interview & questionnaire

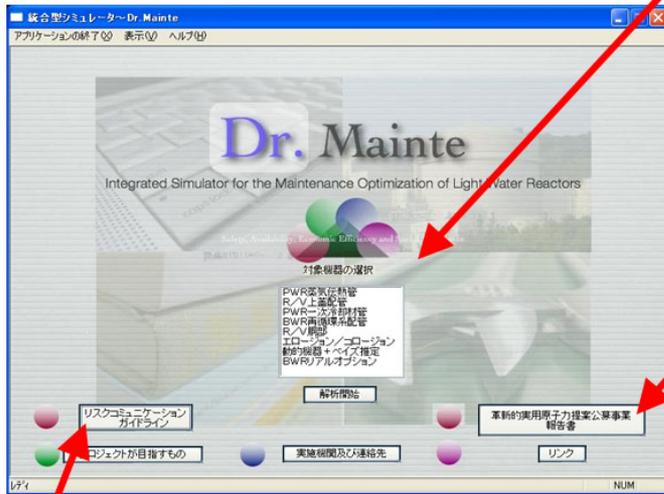
■ Results of the research

- (1) Generally, negative impressions on the shift of conventional inspection to risk-based inspection.
- (2) Strong request for the basis of decision making.
- (3) Also, negative impressions on the comparison of risks.
- (4) Saved costs should be used for safety issues or new energy resources.
- (5) Repeated accidents and industrial accidents have bad impressions.

■ Request to the functions of simulator

- (1) Supply the basis of simulation results to the public
- (2) Consider the effect of repeated accidents in the risk analysis
- (3) Consider the general industrial accidents in the risk analysis

Simulator view



Menu of Analyses

- PWR SG tubes
- RV head nozzles
- PWR PL piping
- BWR PLR piping
- Erosion /Corrosion
- Active components (Bayesian estimate)
- Real Option

Database

- Materials
- Inspections
- Components
- Finance

Guideline of risk communication

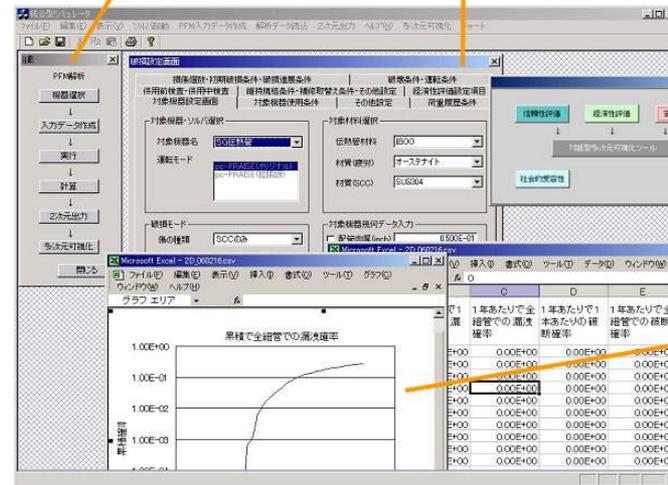
Guideline to account for risk-based maintenance to public.

Start Screen

● **Analysis step view**
Where we are in the total process of analysis ?

● **Dialog of data input**
Data input by the user.

● **Achievements view**
Show the completed analyses.



● **Table & graph view**
Output tables and graphs of simulated results.

Input and Output Screen

■ Summary

- (1) Dr. Maitne an integrated simulator to optimize maintenance activities in LWRs has been successfully established to evaluate various maintenance strategies quantitatively in terms of **Safety, Availability, Economic efficiency, Environmental impact and Social acceptance.**
- (2) “**Interactive divided multi-dimensional visualization method**” using **neural network technique** has been developed to support decision makings efficiently to search and find out the optimum solution of multi-objective problems.
- (3) More recently Dr. Mainte is expanding the field of application to **on-line monitoring and social science issues.**

■ Publications & Presentations (1)

- [1] 匂坂充行, 磯部仁博, 吉村忍, 矢川元基, “確率論的破壊力学に基づく蒸気発生器伝熱管メンテナンス戦略の定量評価”, 日本原子力学会誌, Vol.42, No.12 (2000).
- [2] Y. Isobe, M. Sagisaka, S. Yoshimura, et al., “Risk-benefit analyses of SG tube maintenance strategies based on probabilistic fracture mechanics,” Nucl. Eng. Des., 207, 287-298 (2001).
- [3] 匂坂充行, 磯部仁博, 吉村忍, 矢川元基, “確率論的破壊力学と財務的手法を用いた蒸気発生器伝熱管メンテナンス戦略の経済性評価”, 日本原子力学会和文論文誌, Vol.3, No.2 (2004).
- [4] “Integrated Evaluation of Maintenance Strategies for Steam Generator Tubes Considering Failure Probabilities, Financial Index and Social Acceptance”, NIMS (National Institute for Materials Science) - RIMAP (Risk-Based Inspection and Maintenance Procedure) Risk Based Engineering Workshop, NIMS Tsukuba, 15 March 2004.
- [5] “Economic Evaluation of Maintenance Strategies for Steam Generator Tubes Using Probabilistic Fracture Mechanics and Financial Method”, 5th International Workshop on the Integrity of Nuclear Components, Kyoto, 20-23 April 2004.
- [6] “PFMに基づく実機配管の総合最適メンテナンスに関する技術開発”, 日本原子力学会2005年春の年会, 東海大学, 2005年3月29-31日.
- [7] Y. Isobe, M. Sagisaka, T. Suyama and S. Yoshimura, “Integrated Evaluation of Maintenance Optimization for Pipes in Nuclear Power Plants Based on Probabilistic Fracture Mechanics,” 13th International Conference On Nuclear Engineering (ICONE-13), Beijing, China, May 16-20, 2005.
- [8] M. Sagisaka, Y. Isobe, T. Suyama and S. Yoshimura, “Optimization of Maintenance Strategies for Pipes in Nuclear Power Plants by PFM Approach”, 18th International Conference on Structural Mechanics in Reactor Technology (SmiRT-18), Beijing, China, August 7-12, 2005..
- [9] 磯部仁博, “PFMに基づく軽水炉保全戦略の策定”, 日本溶接協会, 第35回原子力発電設備に関する国内シンポジウム, 化学会館(東京), 2005年6月10日
- [10] “軽水炉保全最適化のための統合型シミュレータに関する技術開発”, 日本原子力学会2005年秋の大会, 八戸工業大学, 2005年9月13-15日
- [11] 磯部仁博, “軽水炉保全最適化のための統合型シミュレータに関する技術開発”, 電気学会 電力機器絶縁診断の経済性評価調査専門委員会, 誘電・絶縁材料技術委員会, 名古屋東桜会館, 2005年11月29日.
- [12] “PFMに基づく軽水炉保全最適化のための統合型シミュレータに関する技術開発 (2)”, 日本原子力学会2006年春の年会, 日本原子力研究開発機構 大洗研究開発センター, 2006年3月24-26日.
- [13] “Maintenance Optimization of LWRs Based on PFM Analysis”, 6th Asian International Symposium on the Structural Integrity of Nuclear Components (ASINCO-6), Kenting Taiwan, April 23-27, 2006.
- [14] S. Yoshimura, K. Furuta, Y. Isobe, M. Sagisaka, et al., “An Integrated Simulator for the Maintenance Optimization of Light Water Reactors”, 8th International Conference on Probabilistic Safety Assessment and Management (PSAM8), New Orleans, USA, May 14-19, 2006.
- [15] 磯部仁博, “軽水炉保全最適化のための統合型シミュレータに関する技術開発”, 電気学会, 原子力リスクマネジメント技術調査専門委員会, 日本交通協会 (東京), 2006年5月24日..
- [16] S. Yoshimura, K. Furuta, Y. Isobe, M. Sagisaka, et al., “Maintenance Optimization of LWRs based on PFM analysis”, ASME PVP 2006, Vancouver, Canada, July 23-27, 2006.
- [17] S. Yoshimura, K. Furuta, Y. Isobe, M. Sagisaka, et al., “Maintenance Optimization of LWRs based on risk and financial analyses”, ICONE 14, Miami, USA, July 17-20, 2006.
- [18] S. Yoshimura, K. Furuta, M. Sagisaka, Y. Isobe, et al., “Integrated Maintenance Optimization of LWRs based on PFM analysis”, Safety and Reliability Conference (ESREL 2006), Estoril, Portugal, September 18-22, 2006.
- [19] “軽水炉保全最適化のための統合型シミュレータに関する技術開発”, 日本原子力学会2006年秋の大会, 北海道大学, 2006年9月27-29日.
- [20] 吉村忍, 古田一雄, 磯部仁博, 匂坂充行, 野田満靖, 秋葉博, “軽水炉保全最適化のための統合型シミュレータに関する技術開発”, 第7回最適化シンポジウム2006, 淡路夢舞台国際会議場, 2006年12月12-13日.

Publications & Presentations (2)

- [21] Y. Isobe, M. Sagisaka, S. Yoshimura, G. Yagawa, "Economic Evaluation of Maintenance Strategies for Steam Generator Tubes Using Probabilistic Fracture Mechanics and a Financial Method," *Solid State Phenomena Vol. 120* (2007) pp.119-126.
- [22] S. Yoshimura, K. Furuta, Y. Isobe, M. Sagisaka, et al., "Maintenance Optimization of LWRs", ICONE 15, Nagoya, Japan, April 22-26, 2007.
- [23] S. Yoshimura, K. Furuta, Y. Isobe, M. Sagisaka, et al., "Integrated Maintenance Optimization of LWRs Based on PFM Analysis", 10th international Conference on Applications of Statistics and Probability in Civil Engineering (ICASP10), Kashiwa Campus, The U. of Tokyo, July 31-August 3, 2007.
- [24] 吉村忍, 古田一雄, 磯部仁博, 匂坂充行, 野田満靖, 秋葉博, "軽水炉保全最適化のための統合型シミュレータに関する技術開発," 日本保全学会第4回学術講演会要旨集, 福井大学, 2007年7月2-3日.
- [25] 熊野秀樹, 原哲也, 匂坂充行, 磯部仁博, "配管保全への確率論的手法の適用性評価," 火力原子力発電 60(6), 575-579 (2009).
- [26] Y. Kanto, K. Onizawa, H. Machida, Y. Isobe, S. Yoshimura, "Recent Japanese Research Activities on Probabilistic Fracture Mechanics for Pressure Vessel and Piping of Nuclear Power Plant," *International Journal of Pressure Vessels and Piping*, Vol.87, pp.11-16 2010.
- [27] Y. Isobe and M. Sagisaka, "Dr. Mainte: An Integrated simulator for Optimization of Maintenance Strategies of Light Water Reactors", ICONE 18, Xi'an, China, May 17-21, 2010.
- [28] 高坂徹, 佐久太郎, 磯部仁博, 吉村忍, "ニューラルネットワークと多次元可視化ツールを用いた企業における従業員モチベーション要因分析と設計", 第二回システム創成学術講演会, 東京大学, 2009年12月14-15日.
- [29] 吉村忍, 古田一雄, 磯部仁博, 匂坂充行, 野田満靖, 秋葉博, "軽水炉保全最適化のための総合型シミュレータDr. Mainteの開発", 日本原子力学会和文論文誌, Vol. 9, No. 2, p. 125-138 (2010). 【平成22年度(2010年度)日本原子力学会賞(論文賞)】
- [30] 磯部仁博, "軽水炉保全最適化のための総合型シミュレータDr. Mainte", 日本原子力学会2010年秋の大会, 計算科学技術部会企画セッション, 北海道大学, 2010年9月15-17日.
- [31] 高坂徹, 佐久太郎, 磯部仁博, 吉村忍, "ニューラルネットワークと多次元可視化ツールを用いた企業における従業員モチベーション要因分析と設計," 日本経営工学会秋季研究大会予稿集, vol.2010, pp.210-211.
- [32] 高坂徹, 佐久太郎, 磯部仁博, 吉村忍, "従業員のモチベーション要因分析とその向上における非線形データ解析/多次元可視化ツールの応用," 日本リスク研究学会年次大会講演論文集, vol.23, pp.43-48.
- [33] 高坂徹, 匂坂充行, 磯部仁博, 吉村忍, "ニューラルネットワークと多次元可視化ツールを用いた保全最適化の試み", 日本原子力学会2011年春の大会, 福井大学, 2011年3月28-30日.
- [34] 高坂徹, 松本聡司, 磯部仁博, 匂坂充行, 吉村忍, "ニューラルネットワークと多次元可視化ツールを用いた保全最適化の試み(2)", 日本原子力学会2011年秋の大会, 北九州国際会議場, 2011年9月20-22日.
- [35] Y. Isobe, M. Sagisaka, J. Etoh, T. Kosaka and S. Yoshimura, "Dr. Mainte: An integrated simulator to optimize maintenance strategies of light water reactors", *International Conference on Materials and Reliability 2011*, Busan, Korea, November 20-22, 2011
- [36] 高坂徹, 松本聡司, 磯部仁博, 匂坂充行, 吉村忍, "ニューラルネットワークと多次元可視化ツールを用いた保全最適化の試み(3)", 日本原子力学会2012年春の大会, 福井大学, 2012年3月19-21日.
- [37] 高坂徹, 松本聡司, 磯部仁博, 匂坂充行, 吉村忍, "軽水炉保全最適化のための統合型シミュレータDr. Mainteによる作業環境の改善検討", 日本原子力学会2012年秋の大会, 広島大学, 2012年9月19-21日.
- [38] リスク活用のための確率論的破壊力学技術—基礎と応用—(日本溶接協会) 2012.
- [39] 磯部仁博, 江藤淳二, 松永嵩, 匂坂充行, 松本聡司, 高坂徹, 吉村忍, "軽水炉保全最適化シミュレーションツール Dr. Mainte を用いたヒューマンエラーの影響とその低減効果の検討", 日本原子力学会2013年秋の大会, 八戸工業大学, 2013年9月3-5日.
- [40] 磯部仁博, 匂坂充行, 江藤淳二, 松永嵩, 松本聡司, 高坂徹, 吉村忍, "軽水炉保全最適化のための統合型シミュレータ Dr. Mainte", 日本保全学会 第11回学術講演会, 八戸工業大学, 2014年9月23-25日.