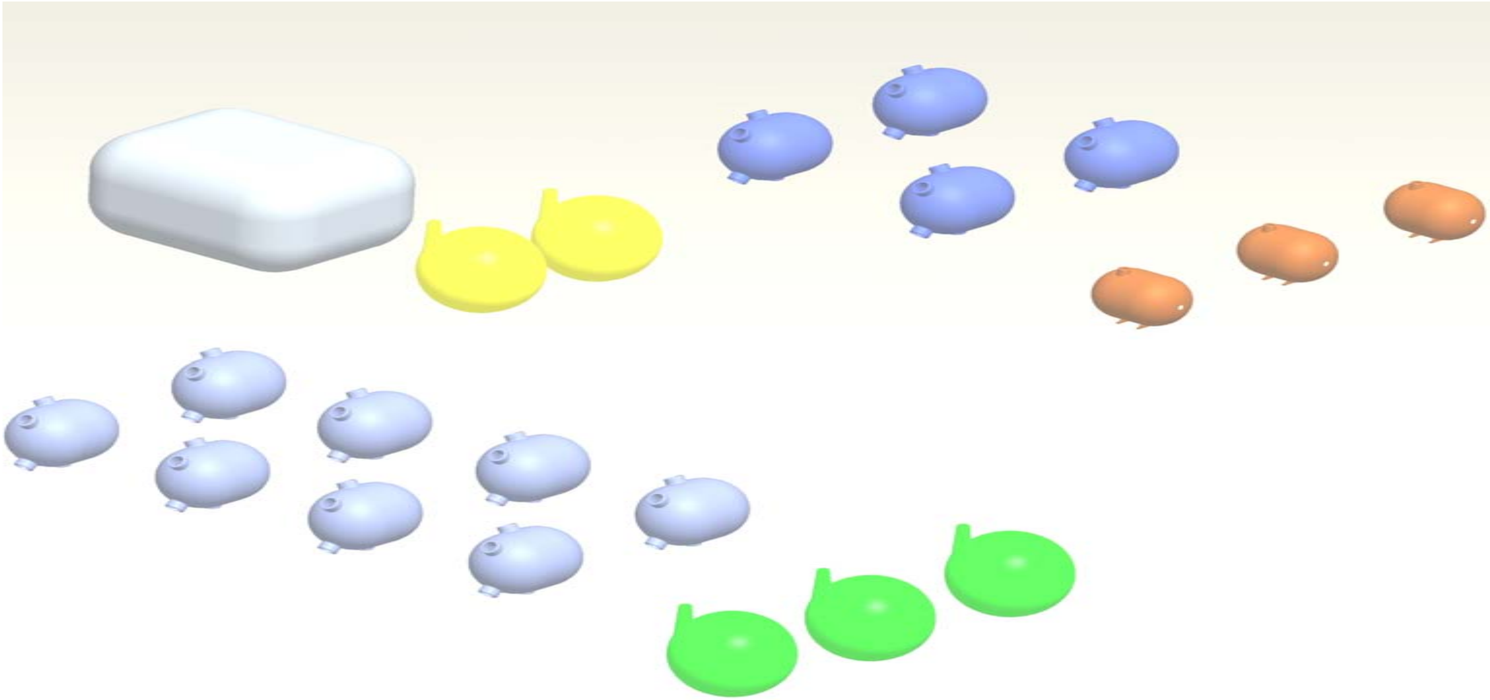
Degradation Analysis and Risk-Informed Management of Feedwater System in Nuclear Power Plants



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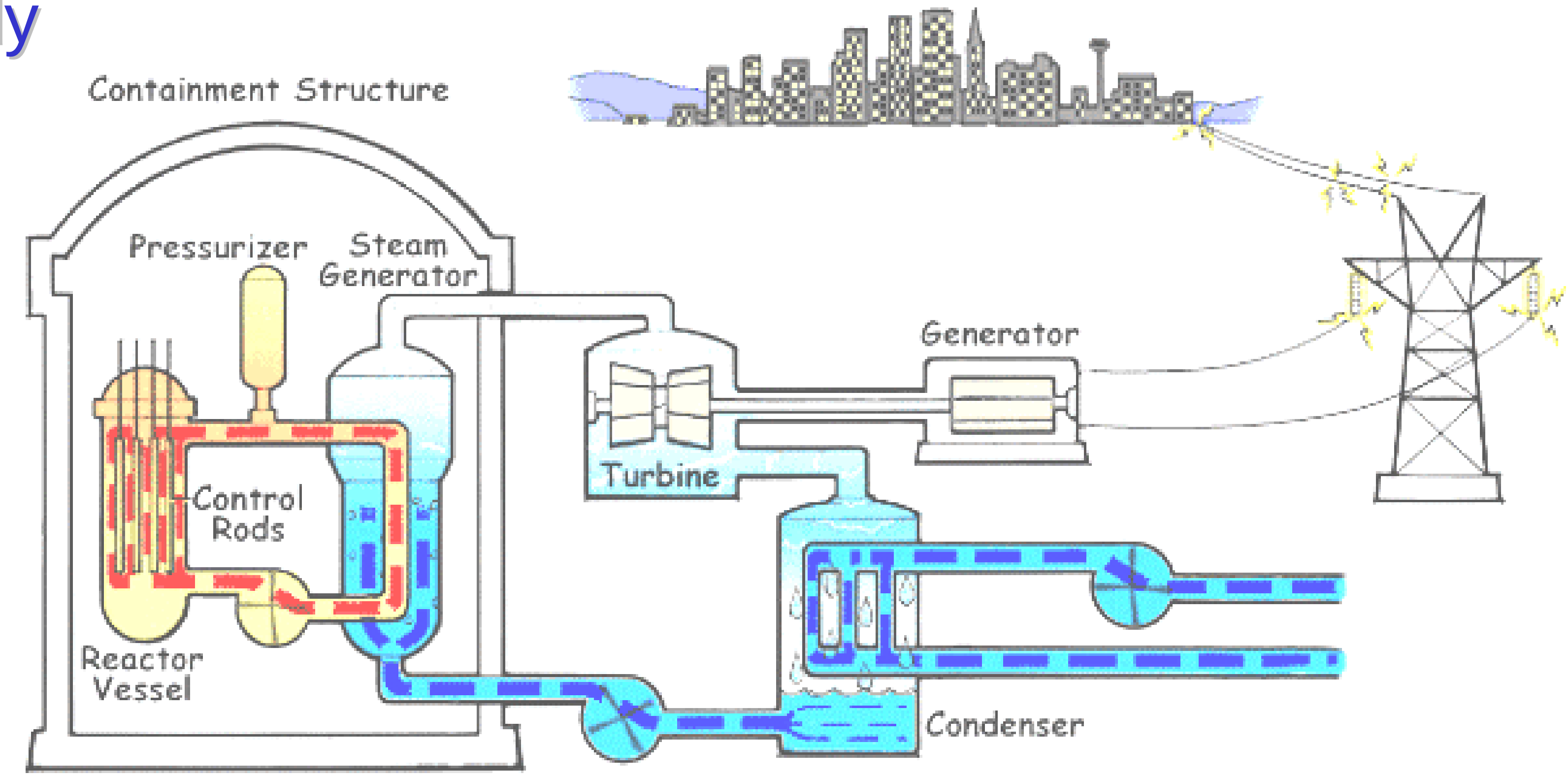
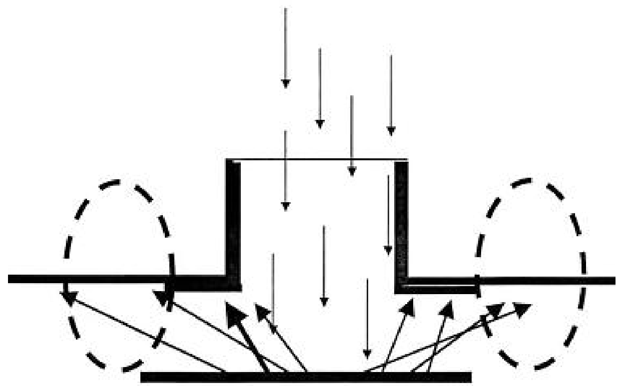
Contents

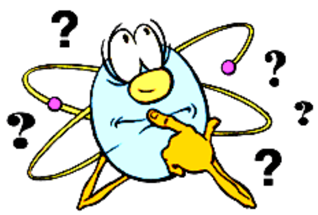
- Degradation or Aging Mechanisms of Feedwater Heaters
- Formulas for Prediction Degradation Rate of Heater-Wall
- Probabilistic Analysis of Individual Feedwater Heaters
- Risk Ranking of Components of a Feedwater System
- Case Study

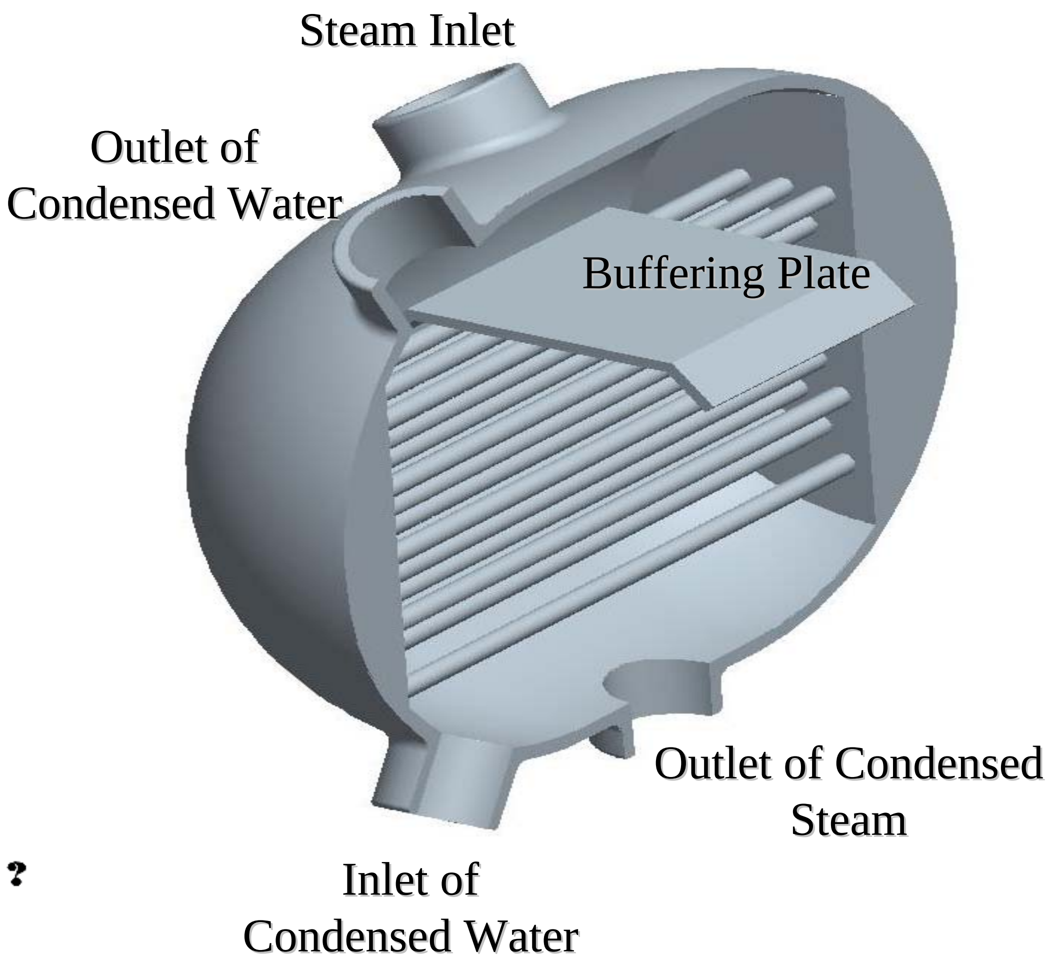


Degradation Phenomenon of Feedwater Heaters

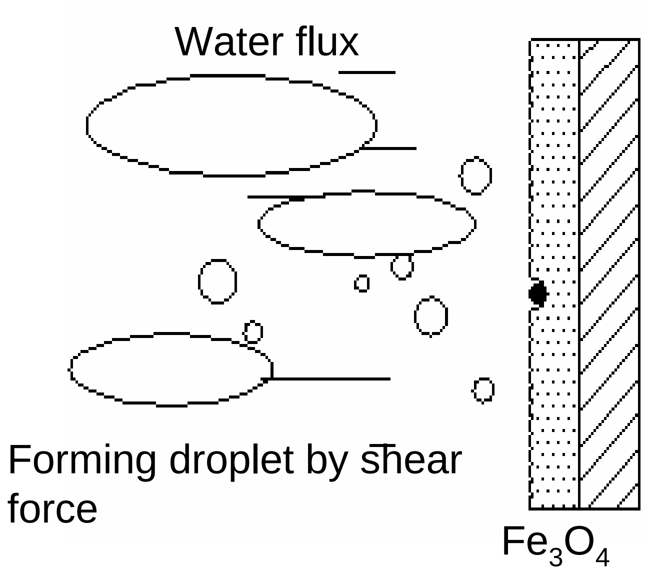


Flow Accelerated Corrosion (FAC) at the Steam Inlet of Heater (Reflected Steam Impact from Buffering Plate)

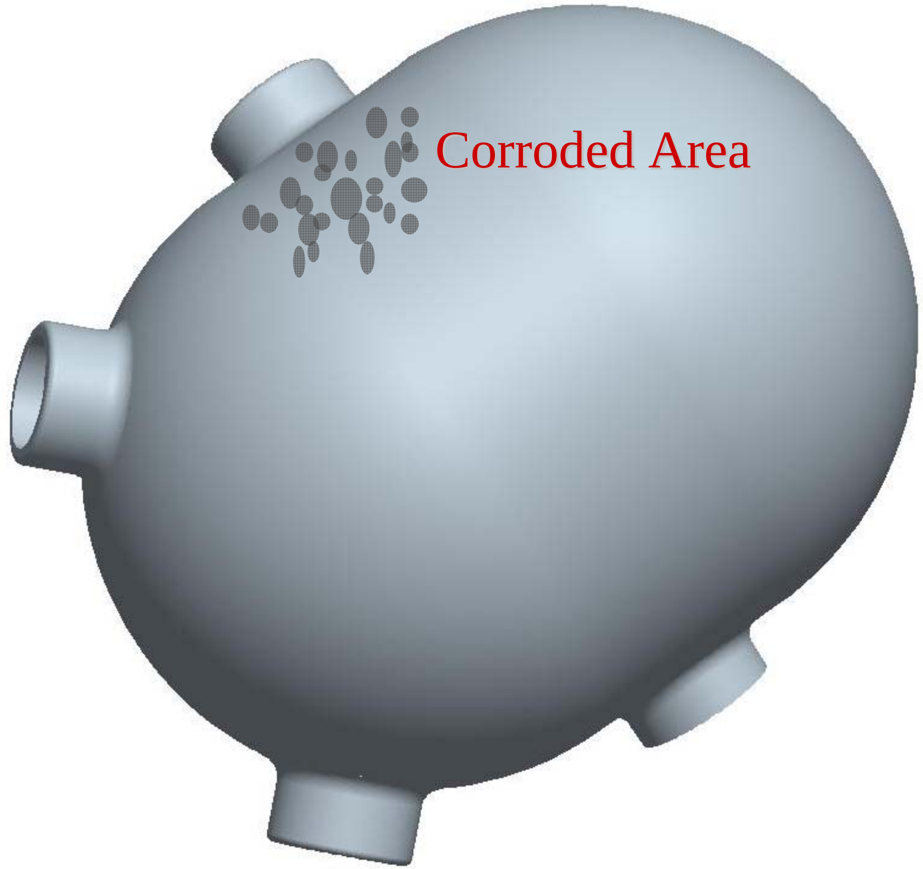




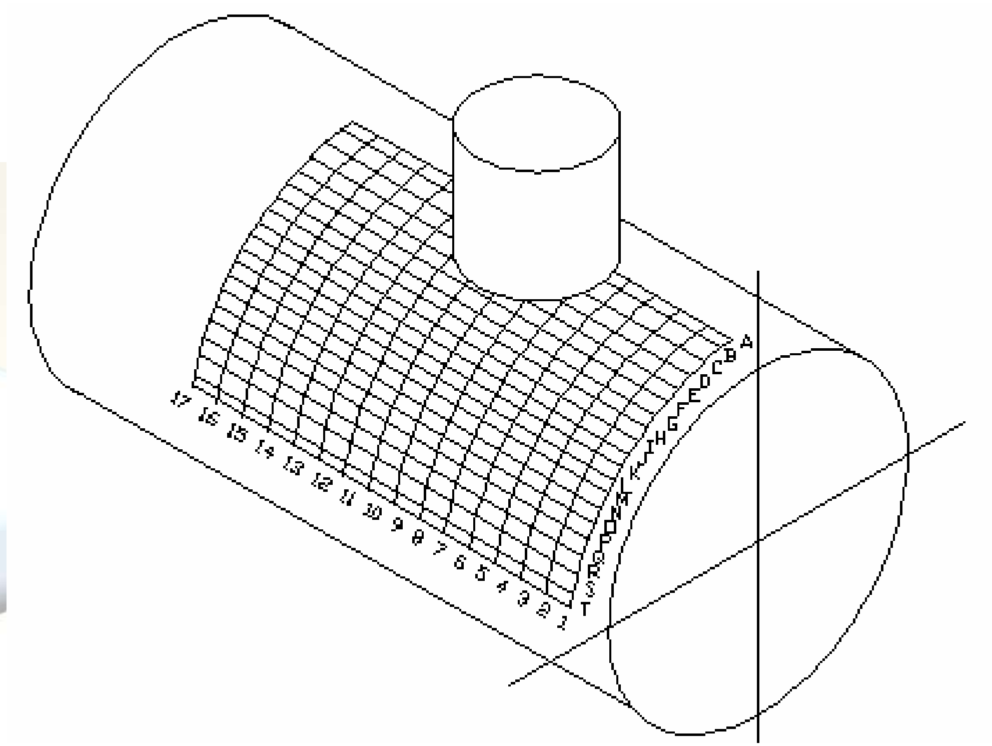
Aging Mechanism



Two–Phase FAC



NDT Examination of Heaters: Point-by-Point Method

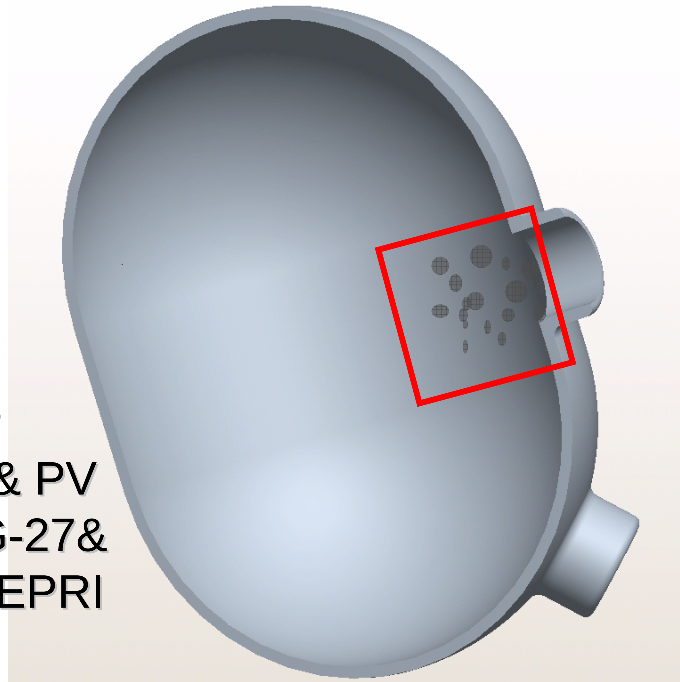


Examination Grids:

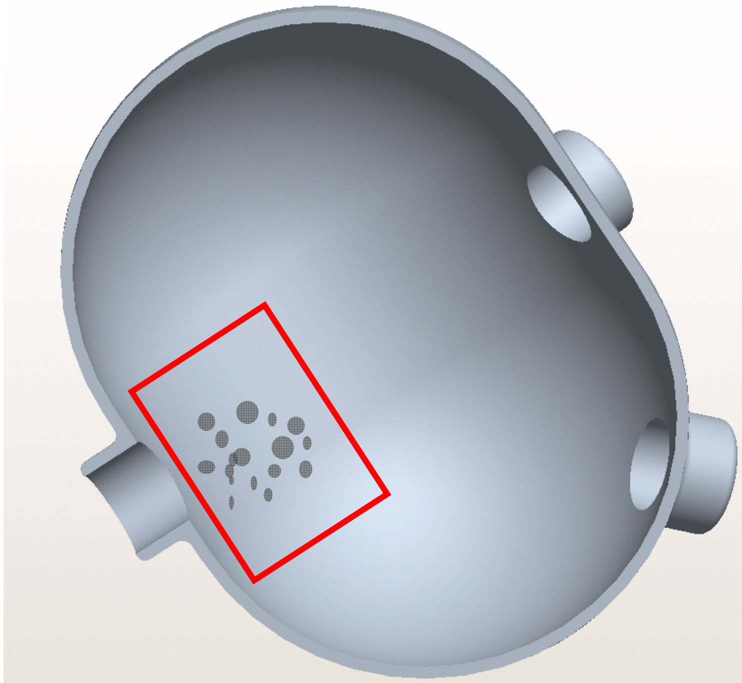
Divide the Shell Side of Steam Inlet to L1, L2, R1 and R2 Areas

3-inch-long Grids expanded to twice the diameter of inlet tube at both sides

Code-Based Safety Assessment



Make Required Repair according to ASME B & PV Sec VIII, Division 1 UG-27& Suggestions made by EPRI

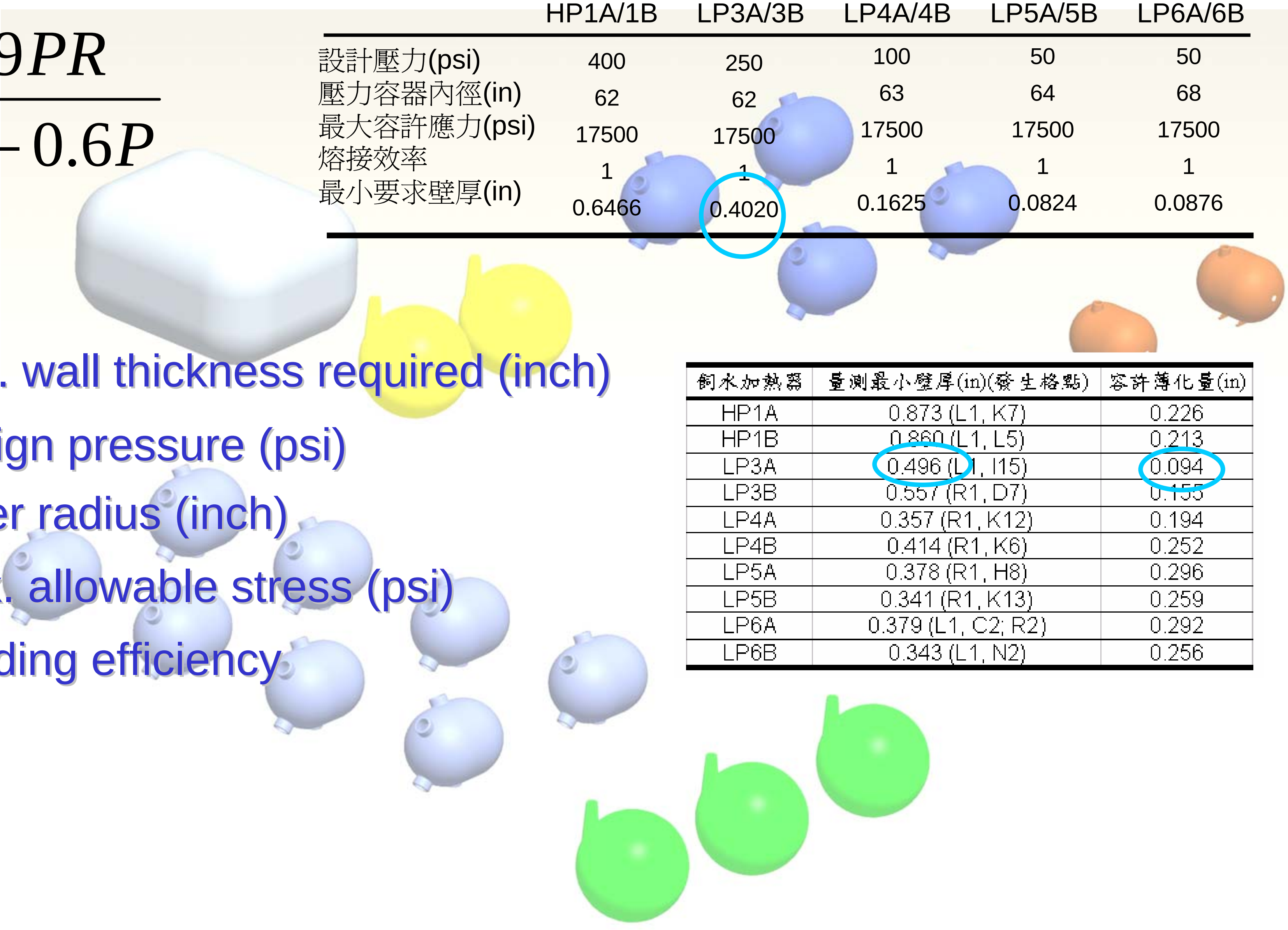


基本資料			
測件名稱	FW-LP3A-L1		
材質	SA-515-70	設計規範	ASME VIII
管徑	63”	設計壓力	250 psi
公稱壁厚	0.542”	設計溫度	405 ˚F
最小壁厚	0.492”		
蒸汽乾度	0.88		
殼側薄化率(mil/yr)			
殼側本體	5.8		

Wall-Thickness Required by ASME B & PV Sec VIII Division 1 UG-27

$$t_L = \frac{0.9PR}{SE - 0.6P}$$

	HP1A/1B	LP3A/3B	LP4A/4B	LP5A/5B	LP6A/6B
設計壓力(psi)	400	250	100	50	50
壓力容器內徑(in)	62	62	63	64	68
最大容許應力(psi)	17500	17500	17500	17500	17500
熔接效率	1	1	1	1	1
最小要求壁厚(in)	0.6466	0.4020	0.1625	0.0824	0.0876



t_L: min. wall thickness required (inch)

P: design pressure (psi)

R: inner radius (inch)

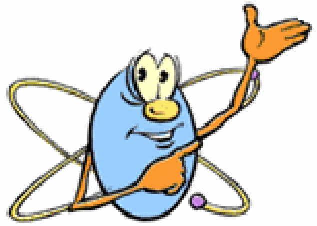
S: max. allowable stress (psi)

E: welding efficiency

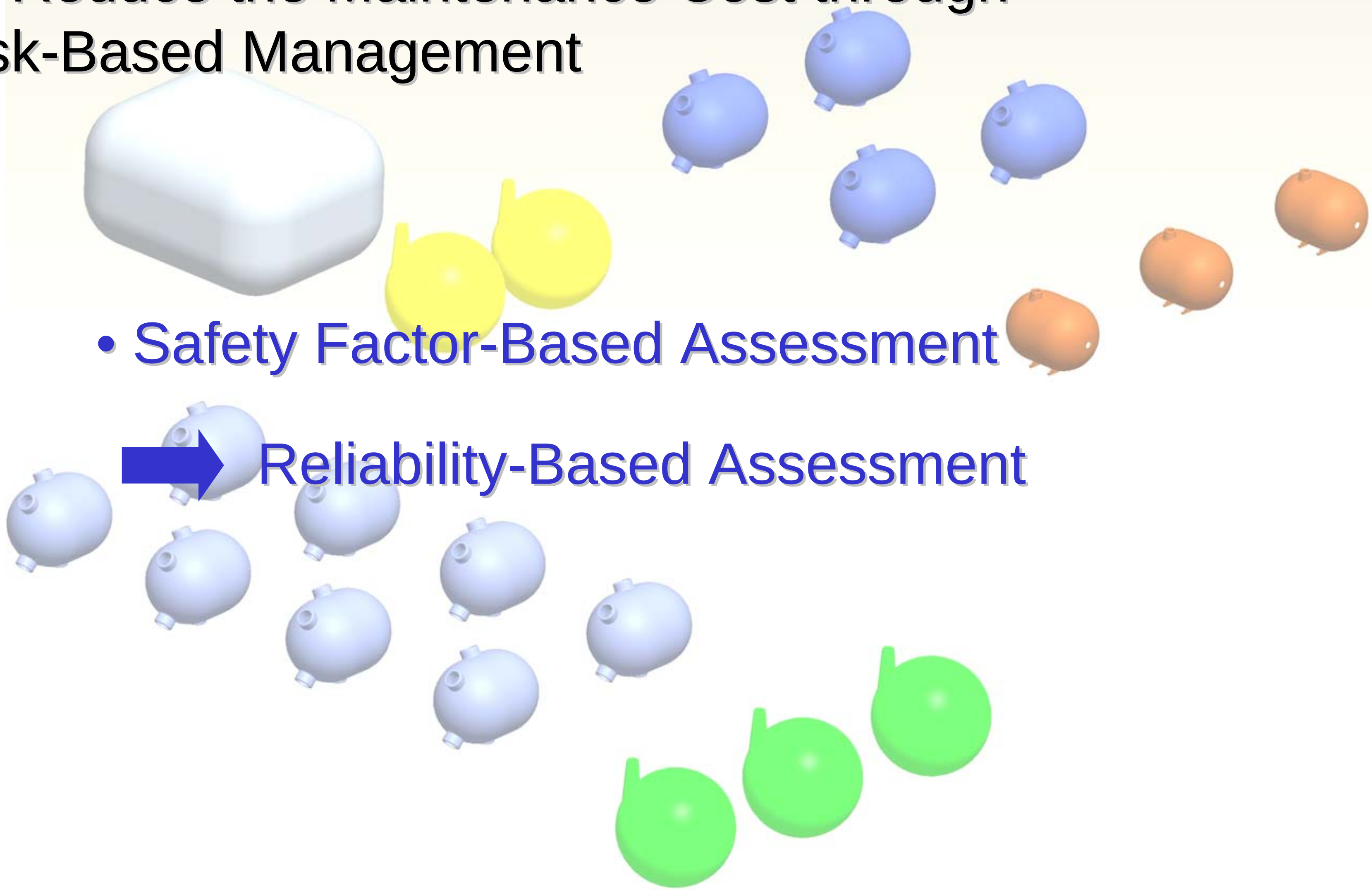
飼水加熱器	量測最小壁厚(in)(發生格點)	容許薄化量(in)
HP1A	0.873 (L1, K7)	0.226
HP1B	0.860 (L1, L5)	0.213
LP3A	0.496 (L1, I15)	0.094
LP3B	0.557 (R1, D7)	0.155
LP4A	0.357 (R1, K12)	0.194
LP4B	0.414 (R1, K6)	0.252
LP5A	0.378 (R1, H8)	0.296
LP5B	0.341 (R1, K13)	0.259
LP6A	0.379 (L1, C2; R2)	0.292
LP6B	0.343 (L1, N2)	0.256

Present Research

To Replace the Deterministic Assessment by Risk-Based Assessment



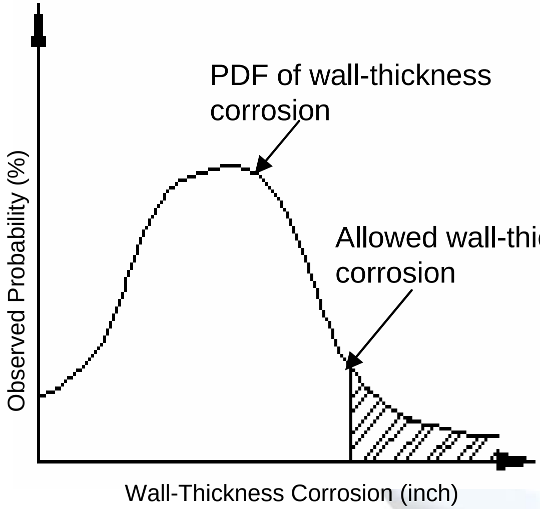
To Reduce the Maintenance Cost through Risk-Based Management



- Safety Factor-Based Assessment

➡ Reliability-Based Assessment

• Incorporating Aging Mechanism into QRA



FTA, ETA

+

$$\mathrm{FV}(q_j) = \frac{p\left(\bigcup_{i=1}^{m} \mathrm{MCS}_i^j\right)}{p\left(\bigcup_{k=1}^{n} \mathrm{MCS}_k\right)}$$

$$\mathrm{RAW}\left(q_j\right) = \frac{R_j^+}{R_o}$$

$$\mathrm{DIM}\left(q_j\right) = \frac{\frac{\partial R}{\partial q_j} dq_j}{\sum_k \frac{\partial R}{\partial q_k} dq_k}$$

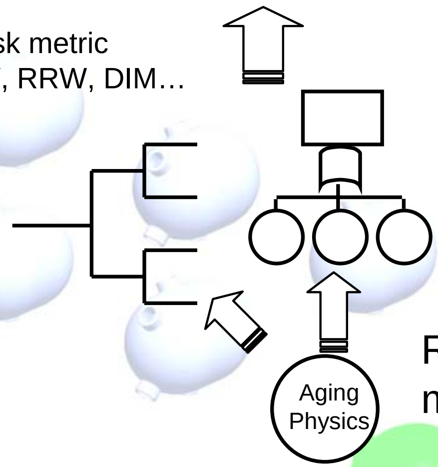
=

Risk Ranking

Importance Measure

Importance measure…
& Risk ranking

Risk metric
FV, RRW, DIM…



Reliability
model

FAC Empirical Models

1. KWU/KR Model: Siemens Co. & WATHEC Software Package

2. ERPI-CH Model: EPRI & CHECWORKS Software Package (not released to public)

3. BRT-Cicero Model: Electricite de France by Cicero Test Loop (not released to public)

⋮

KWU Single-Phase FAC Empirical Model

$$\Delta\phi_R = 6.35 k_c \left(B \cdot e^{N \cdot W} \left[1 - 0.75 \cdot (pH - 7)^2 \right] \cdot 1.8 \cdot e^{-0.118 g} + 1 \right) \cdot f(t)$$

$$B = -10.5\sqrt{h} - \left(9.375 \times 10^{-4} T^2\right) + 0.79T - 132.5$$

$$N = -0.0875h - \left(1.275 \times 10^{-5} T^2\right) + \left(1.078 \times 10^{-2} T\right) - 2.15$$

$$f(t) = 0.9999934 - 3.356901 \times 10^{-7} t - 5.624812 \times 10^{-11} t^2 + 3.849972 \times 10^{-16} t^3$$

$\Delta\phi_R =$ FAC rate (μg/cm²h)

$k_c =$ geometric factor (0.8 for "T" junction)

$W =$ fluid velocity (m/s)

$pH =$ pH value

$g =$ oxygen content (μg/kg)

$h =$ Cr and Mo in steel (0% for SA515-70)

$T =$ temperature ($^\circ$K)

$t =$ exposure time (1.5 yr=13140 hrs per EOC)

KWU Two-Phase FAC Empirical Model

Modified Flow Velocity:

$$W = \frac{\dot{m}}{\rho_w} \frac{1 - x_{st}}{1 - \alpha}$$

$\dot{m}$ = mass flux(kg/m s)

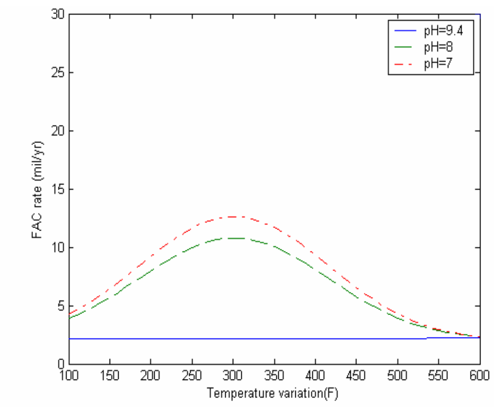
ρ_w = density of compressed liquid (kg/m^3)

x_{st} = steam quality

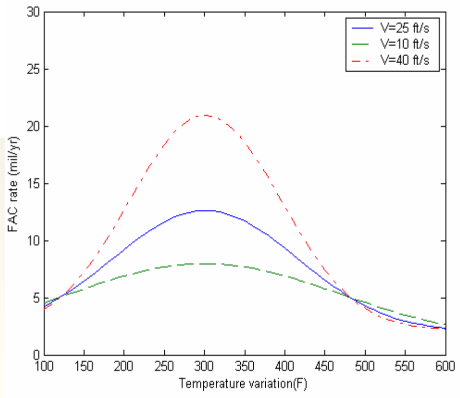
α = void fraction

Parameter Sensitivity Analysis

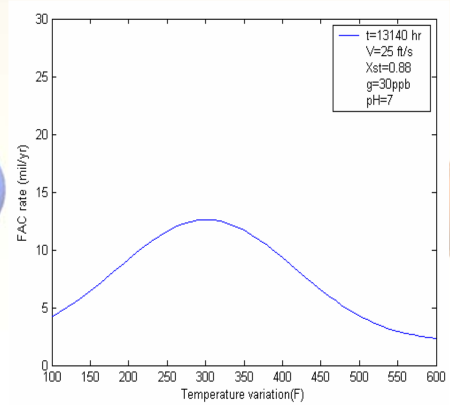
$$\mathrm{KWU} = f\left(pH, g, T, W, x_{st}\right)$$



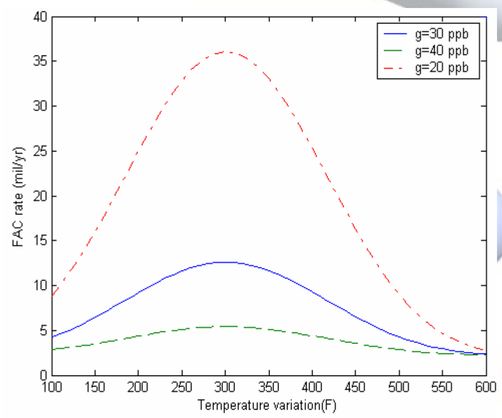
FAC rate-pH



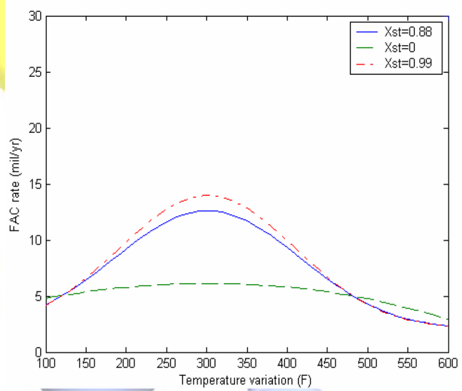
FAC rate-Fluid velocity



FAC rate-Temperature



FAC rate-Oxygen content



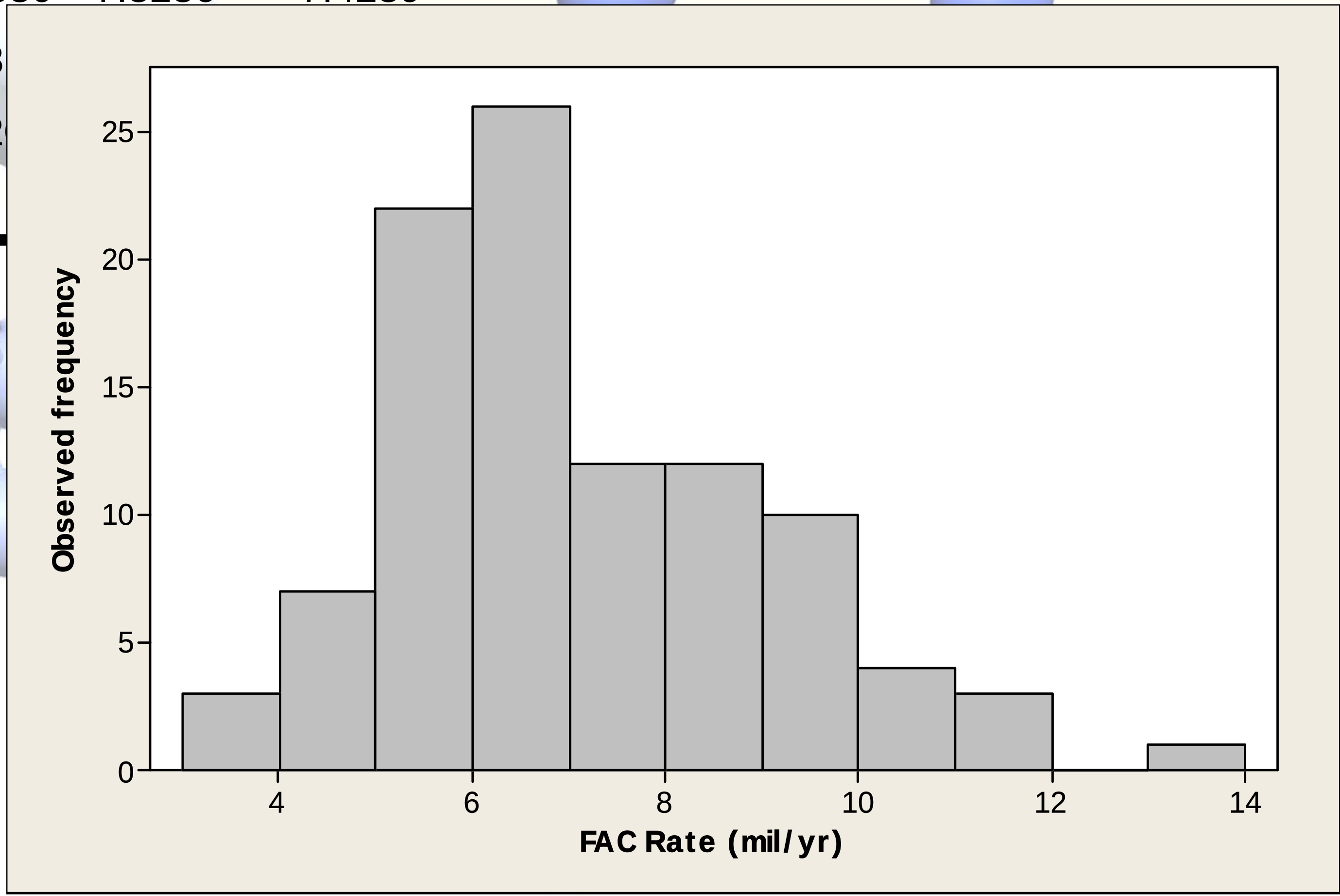
FAC rate-Steam quality

Monte Carlo Simulation of FAC Rate

Parameter	Symbol	Mean value	Standard deviation	Distribution
Temperature (°F)	T	405	40.5	Normal
Exposure time (hr)	t	13140	N/A	Point estimate
Oxygen content (ppb)	g	30	3	Normal
Water chemistry (pH)	pH	7	0.7	Normal
Steam quality	x_{st}	0.88	N/A	Point estimate
Piping geometry	k_c	0.8	N/A	Point estimate
Cr + Mo in %	h	0	N/A	Point estimate
Fluid velocity (ft/s)	W	13.2	13.2	Normal

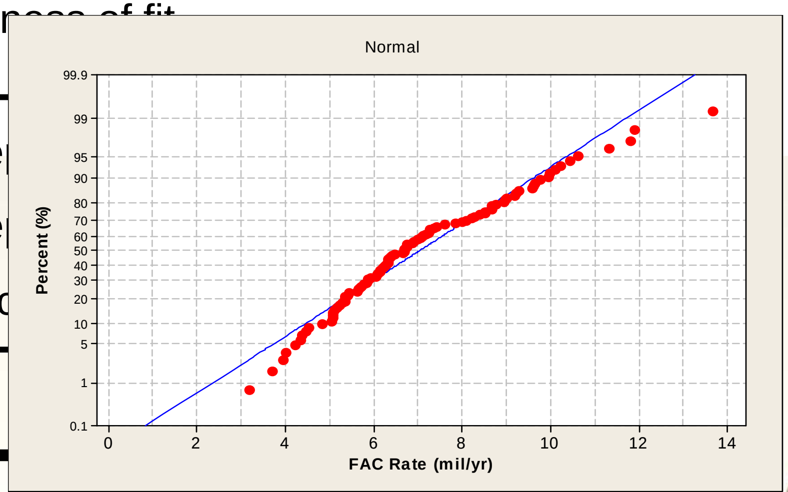
Distribution of Thinning Rate

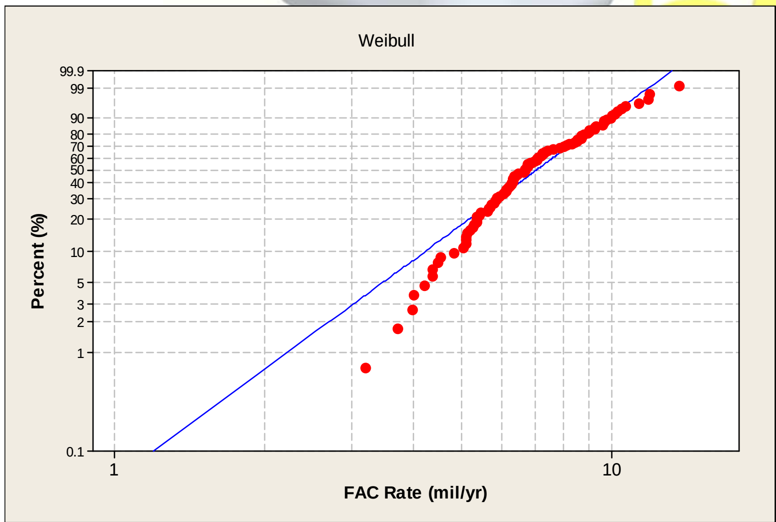
Temperature	Fluid Velocity	g	pH	FAC Rate (mil/yr)
387	11.6321	31.9058	6.3728	6.0569
337	10.2929	28.1958	7.0946	9.2151
410	14.5020	31.6536	6.9027	6.3281
416	12.5154	26.7005	6.1856	8.2137
358	13.6321	30.2580	7.8286	7.4289
453	13.5090	23.98		
453	13.2283	28.52		
⋮				

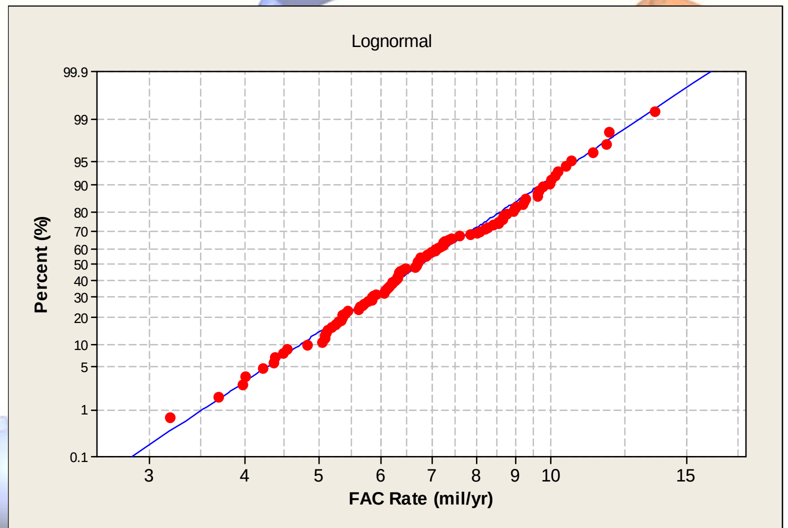


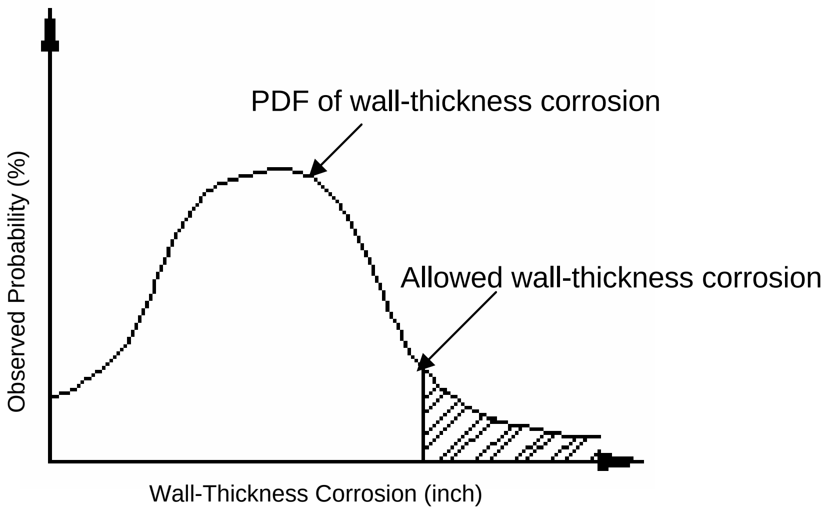
Goodness-of-Fit Test

Distribution	Test value $\alpha = \sum_{i=1}^{11} \frac{(E_i - O_i)^2}{E_i}$	Goodn
Normal	13.7310	Acce
Lognormal	6.4282	Acce
Weibull	16.8625	Not acc
Critical value $\alpha_{0.95,8}$	15.5	







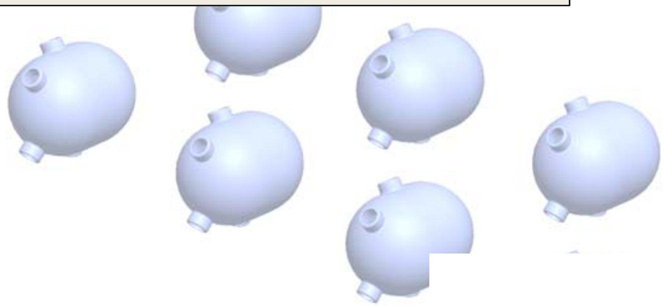


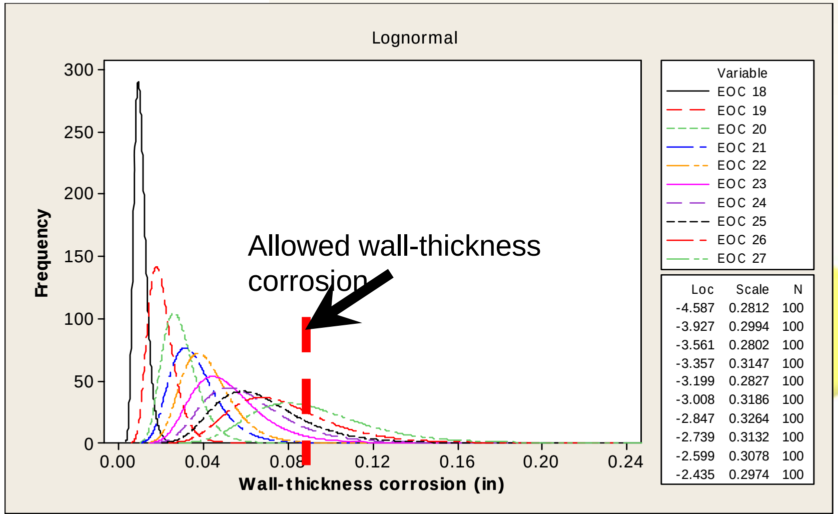
飼水加熱器	量測最小壁厚(in)(發生格點)	容許薄化量(in)
HP1A	0.873 (L1, K7)	0.226
HP1B	0.860 (L1, L5)	0.213
LP3A	0.496 (L1, I15)	0.094
LP3B	0.557 (R1, D7)	0.155
LP4A	0.357 (R1, K12)	0.194
LP4B	0.414 (R1, K6)	0.252
LP5A	0.378 (R1, H8)	0.296
LP5B	0.341 (R1, K13)	0.259
LP6A	0.379 (L1, C2; R2)	0.292
LP6B	0.343 (L1, N2)	0.256

Random-Fixed Reliability Model

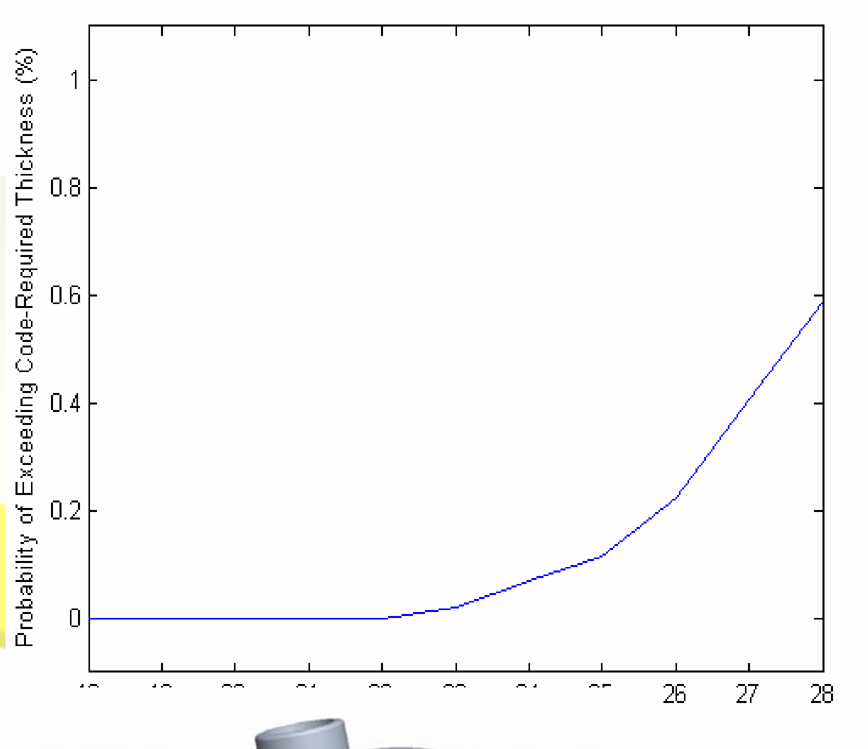
	HP1A/1B	LP3A/3B	LP4A/4B	LP5A/5B	LP6A/6B
設計壓力(psi)	400	250	100	50	50
壓力容器內徑(in)	62	62	63	64	68
最大容許應力(psi)	17500	17500	17500	17500	17500
熔接效率	1	1	1	1	1
最小要求壁厚(in)	0.6466	0.4020	0.1625	0.0824	0.0876

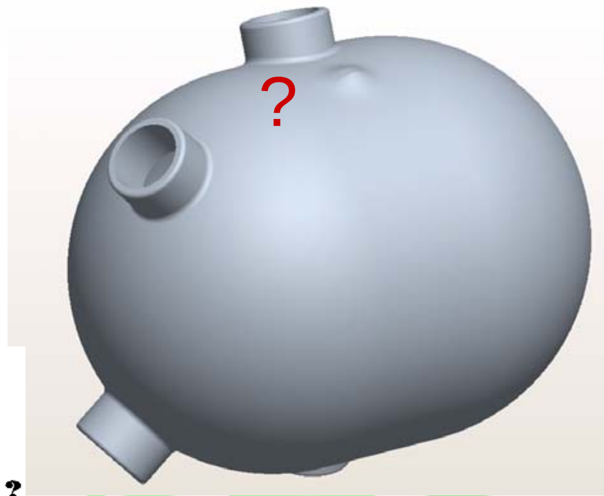
Reliability-Based Aging Assessment

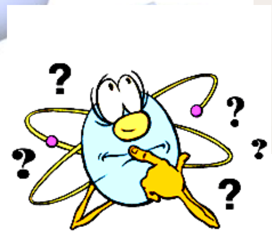


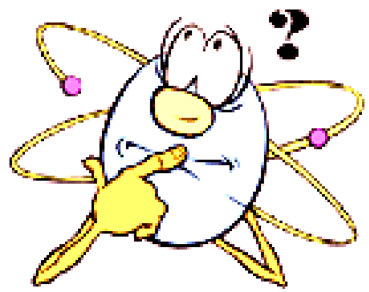


Loc	Scale	N
-4.587	0.2812	100
-3.927	0.2994	100
-3.561	0.2802	100
-3.357	0.3147	100
-3.199	0.2827	100
-3.008	0.3186	100
-2.847	0.3264	100
-2.739	0.3132	100
-2.599	0.3078	100
-2.435	0.2974	100









Risk Metric & Importance Measures

Risk Metric: A Function of Frequencies of Initiating Events & Conditional Probabilities of Failure Modes of SSCs

$$R = h(f_{\mathrm{IE}i}, q_j)$$

(i) FV IM: Focus on Weight of Failure of Cutsets containing BE$_j$

$$\mathrm{FV}(q_j) = \frac{R_0 - R_j^-}{R_0} \quad \text{or} \quad \mathrm{FV}(q_j) = \frac{p\left(\bigcup_{i=1}^{m} \mathrm{MCS}_i^j\right)}{p\left(\bigcup_{k=1}^{n} \mathrm{MCS}_k\right)}$$

Probability of union of all min cutsets (MCS) containing BE$_j$

Nominal risk (probability of all MCSs)

(ii) RAW IM: Focus on Weight (Increase) of Risk owing to BE*j*

$$\mathrm{RAW}\left(q_j\right)=\frac{R_j^+}{R_o}$$

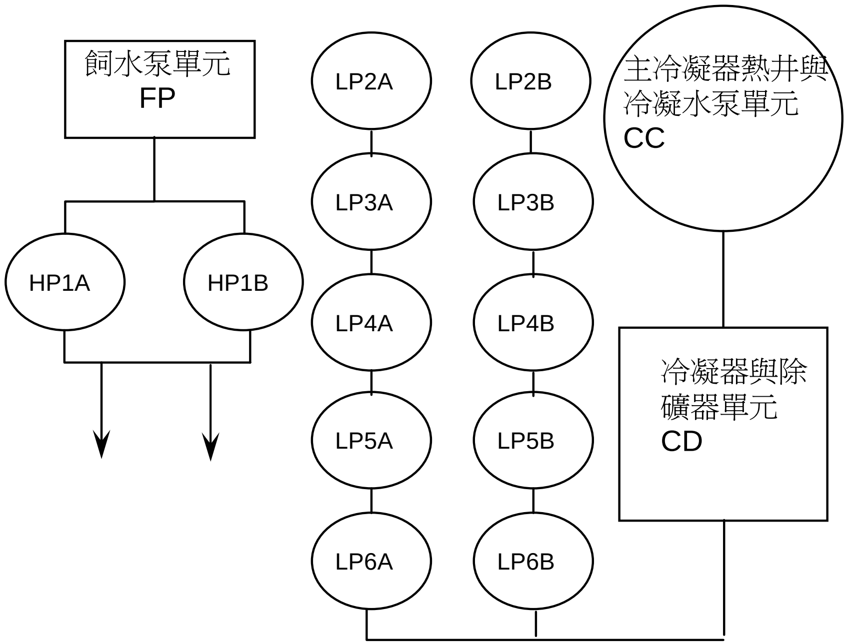
(iii) Differential IM (DIM): Focus on Risk Change due to Variation of BE*j*
(Borgonovo & Apostolakis, 2001)

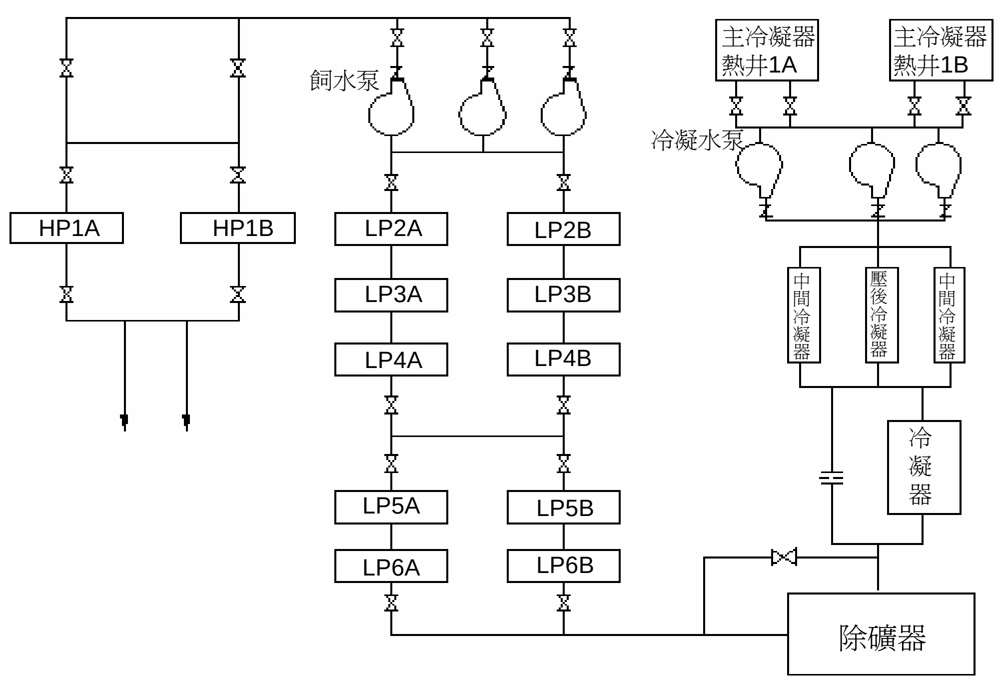
$$\mathrm{DIM}\left(q_j\right)\equiv\frac{dR_{q_j}}{dR}=\frac{\frac{\partial R}{\partial q_j}dq_j}{\sum_k\frac{\partial R}{\partial q_k}dq_k}=\frac{\frac{\partial R}{\partial q_j}}{\sum_k\frac{\partial R}{\partial q_k}} \qquad \delta q_i=\delta q_j \qquad \text{H1}$$

or

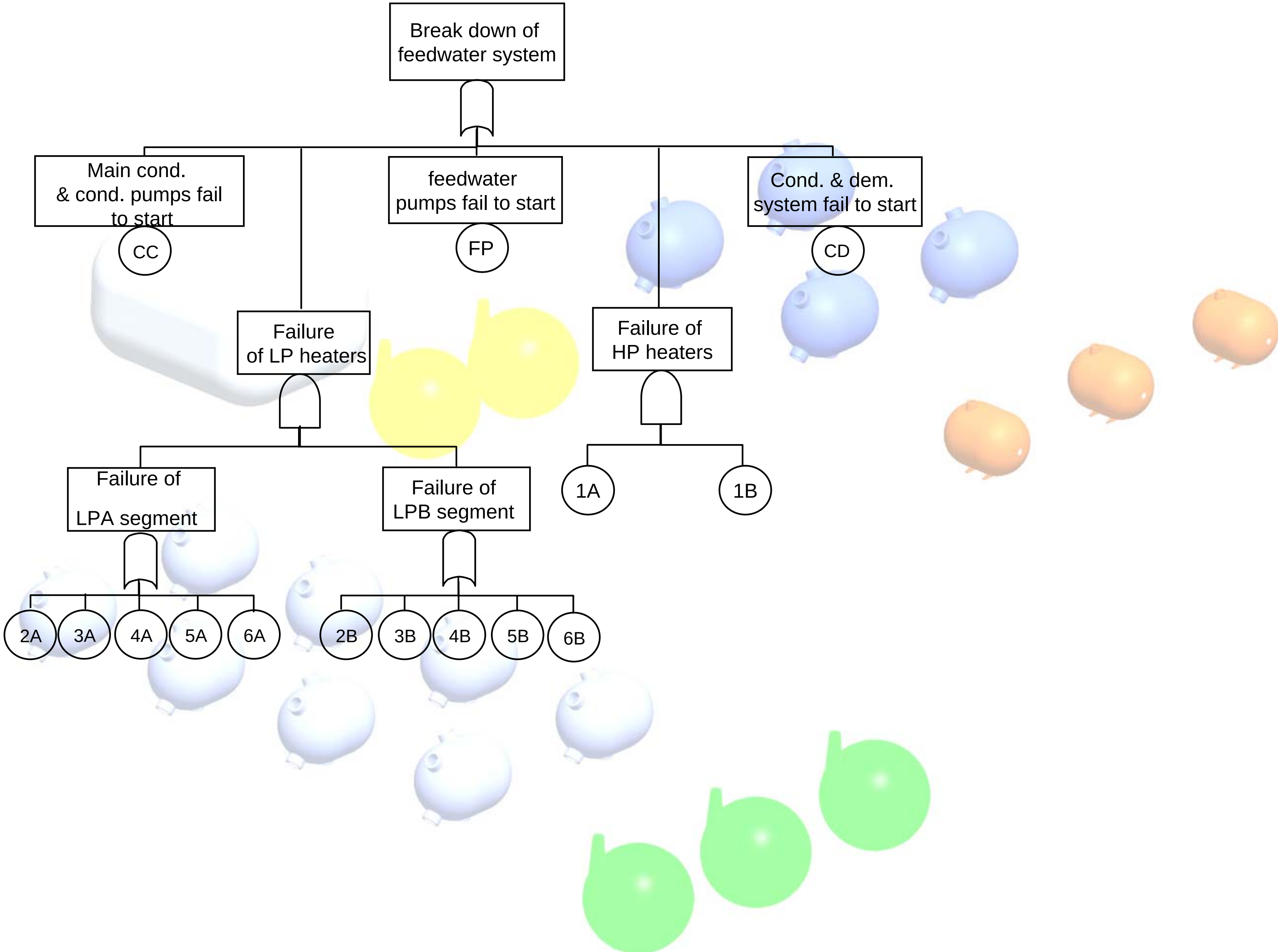
$$\mathrm{DIM}(q_j)=\frac{\frac{\partial R}{\partial q_j}\frac{dq_j}{q_j}q_j}{\sum_k\frac{\partial R}{\partial q_k}\frac{dq_k}{q_k}q_k}=\frac{\frac{\partial R}{\partial q_j}q_j}{\sum_k\frac{\partial R}{\partial q_k}q_k} \qquad \frac{\delta q_i}{q_i}=\frac{\delta q_j}{q_j}=\omega \qquad \text{H2}$$

Case Study: PRA of a BWR Feedwater System





Fault Tree Analysis

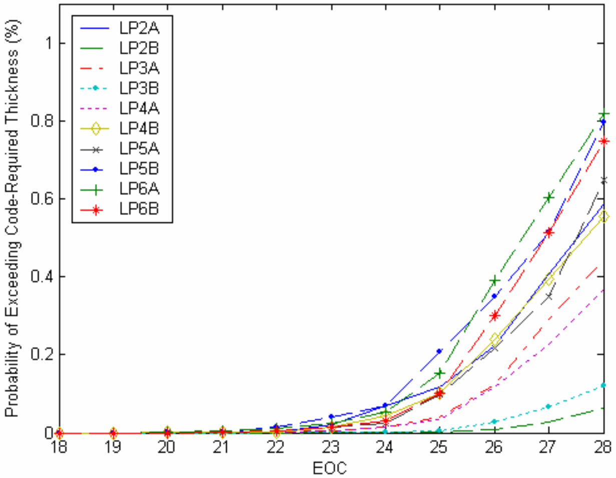


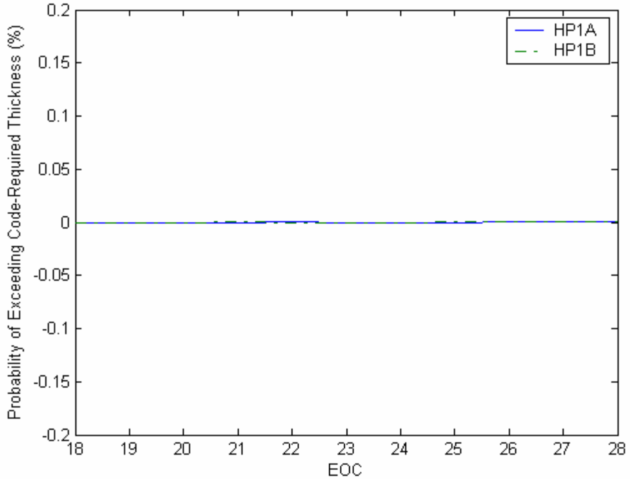
Operational Conditions (by assumption):

FWH	Design pressure (psi)	Design temperature (F)	Fluid velocity (ft/s)	Oxygen Content (ppb)	Water chemistry (pH)	Steam quality (%)	T_L (in)	Wall thickness detected at EOC17 (in)
HP1A	400	475	24.5	35	7	94	0.646	0.873
HP1B	400	475	24.5	35	7	94	0.646	0.860
LP2A	250	405	13.2	30	7	88	0.402	0.496
LP2B	250	405	13.2	30	7	88	0.402	0.557
LP3A	100	350	14.2	25	7	99.9	0.162	0.357
LP3B	100	350	14.2	25	7	99.9	0.162	0.414
LP4A	50	300	15	22	7	98	0.082	0.378
LP4B	50	300	15	22	7	98	0.082	0.341
LP5A	50	300	18.8	22	7	85.5	0.087	0.379
LP5B	50	300	18.8	22	7	85.5	0.087	0.343
LP6A	50	280	18	20	7	90	0.090	0.394
LP6B	50	280	18	20	7	90	0.090	0.415

Numerical Analysis

Component	Event (number)	EOC18	EOC19	EOC20	EOC21	EOC22	EOC23	EOC24	EOC25	EOC26	EOC27	EOC28
FP	FP (1)	0.00164	0.00329	0.00493	0.00657	0.00821	0.00985	0.01148	0.01311	0.01474	0.01636	0.01798
CD	CD (2)	0.00284	0.00568	0.00851	0.01133	0.01414	0.01695	0.01975	0.02254	0.02532	0.02809	0.03086
HP1A	1A (3)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00003
HP1B	1B (4)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00007
LP2A	2A (5)	0.00000	0.00000	0.00001	0.00081	0.00158	0.02170	0.06964	0.11588	0.22303	0.40626	0.58786
LP2B	2B (6)	0.00000	0.00000	0.00000	0.00000	0.00000	0.00017	0.0013	0.00261	0.00850	0.02750	0.06327
LP3A	3A (7)	0.00000	0.00000	0.00003	0.00004	0.00053	0.00643	0.01413	0.03934	0.12429	0.28980	0.44601
LP3B	3B (8)	0.00000	0.00000	0.00000	0.00000	0.00001	0.00038	0.00085	0.00425	0.02676	0.06614	0.12067
LP4A	4A (9)	0.00000	0.00000	0.00001	0.00003	0.00024	0.00374	0.01595	0.03450	0.11722	0.22576	0.36817
LP4B	4B (10)	0.00000	0.00000	0.00006	0.00019	0.00143	0.01387	0.04312	0.10141	0.23916	0.39379	0.55409
LP5A	5A (11)	0.00000	0.00000	0.00001	0.00051	0.00406	0.01360	0.02402	0.09770	0.21715	0.34879	0.64884
LP5B	5B (12)	0.00000	0.00000	0.00005	0.00235	0.01404	0.04104	0.06792	0.20599	0.34911	0.51261	0.79728
LP6A	6A (13)	0.00000	0.00000	0.00007	0.00326	0.00997	0.02537	0.05339	0.15336	0.38959	0.60311	0.81711
LP6B	6B (14)	0.00000	0.00000	0.00000	0.00165	0.00506	0.01414	0.03019	0.10136	0.30057	0.51230	0.74784
CC	CC (15)	0.00434	0.00866	0.01296	0.01724	0.02151	0.02576	0.02999	0.03420	0.03839	0.04256	0.04672





Failure Probability of Series Systems:

$$F_{series} = 1 - (1 - q_1)(1 - q_2)\ldots(1 - q_n)$$

Failure Probability of Parallel Systems:

$$F_{parallel} = q_1 q_2 \ldots q_n$$

Feedwater Pumps

$$F_{FP} = q_1$$

Condenser & De-Mining Units

$$F_{CD} = q_2$$

High-Pressure FW Heaters

$$F_{HP} = q_3 q_4$$

Low-Pressure FW Heaters

$$F_{LP} = [1-(1-q_5)(1-q_7)(1-q_9)(1-q_{11})(1-q_{13})][1-(1-q_6)(1-q_8)(1-q_{10})(1-q_{12})(1-q_{14})]$$

Hot Well & Pump of Main Condensers

$$F_{CC} = q_{15}$$

Risk Metric of Feedwater System

$$
\begin{aligned}
R(q_j) &= 1-(1-F_{FP})(1-F_{CD})(1-F_{LP})(1-F_{HP})(1-F_{CC}) \\
&= F_{LP} + F_{HP} - F_{LP}F_{HP} + F_{FP} - F_{FP}F_{LP} - F_{FP}F_{HP} + F_{FP}F_{LP}F_{HP} \\
&\quad + F_{CD} - F_{CD}F_{LP} - F_{CD}F_{HP} + F_{CD}F_{LP}F_{HP} - F_{FP}F_{CD} + F_{FP}F_{CD}F_{LP} \\
&\quad + F_{FP}F_{CD}F_{HP} - F_{FP}F_{CD}F_{LP}F_{HP} + F_{CC} - F_{LP}F_{CC} - F_{HP}F_{CC} \\
&\quad + F_{LP}F_{HP}F_{CC} - F_{FP}F_{CC} + F_{FP}F_{LP}F_{CC} + F_{FP}F_{HP}F_{CC} - F_{FP}F_{LP}F_{HP}F_{CC} \\
&\quad - F_{CD}F_{CC} + F_{CD}F_{LP}F_{CC} + F_{CD}F_{HP}F_{CC} - F_{CD}F_{LP}F_{HP}F_{CC} + F_{FP}F_{CD}F_{CC} \\
&\quad - F_{FP}F_{CD}F_{LP}F_{CC} - F_{FP}F_{CD}F_{HP}F_{CC} + F_{FP}F_{CD}F_{LP}F_{HP}F_{CC}
\end{aligned}
$$

Example: LP2A at EOC 26 (assuming no repair)

$$
\mathrm{H1:}\quad \mathrm{DIM}(q_5) = \frac{\dfrac{\partial R(q_j)}{\partial (q_5)}}{\displaystyle\sum_{k=1}^{15} \frac{\partial R(q_j)}{\partial q_k}} = 5.64\mathrm{E}-02
$$

$$
\mathrm{H2:}\quad \mathrm{DIM}(q_5) = \frac{\dfrac{\partial R(q_j)}{\partial (q_5)} \cdot q_5}{\displaystyle\sum_{k=1}^{15} \frac{\partial R(q_j)}{\partial q_k} q_k} = 8.59\mathrm{E}-02
$$

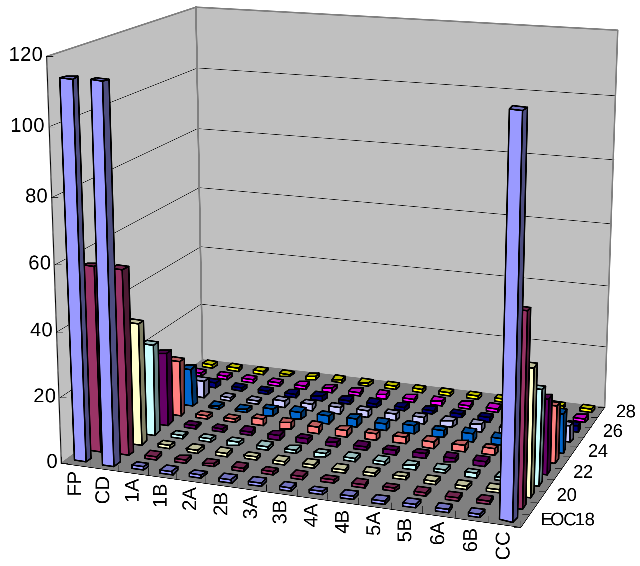
$$\mathrm{RAW}(q_5) = \frac{q_5^{\ +}}{R(q_j)} = 1.3548$$

In $R(q_j)$, delete all terms not related to q_5 to obtain MCS containing BE_5

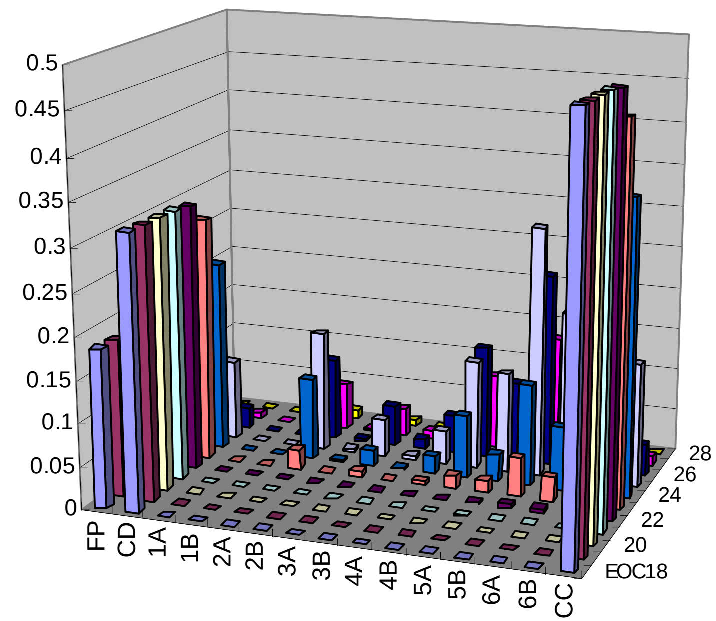
$$\begin{aligned}
R(q_j) &= 1-(1-F_{FP})(1-F_{CD})(1-F_{LP})(1-F_{HP})(1-F_{CC}) \\
&= F_{LP} + \cancel{F_{HP}} - F_{LP}F_{HP} + \cancel{F_{FP}} - F_{FP}F_{LP} - \cancel{F_{FP}}\cancel{F_{HP}} + F_{FP}F_{LP}F_{HP} \\
&\quad + \cancel{F_{CD}} - F_{CD}F_{LP} - \cancel{F_{CD}}\cancel{F_{HP}} + F_{CD}F_{LP}F_{HP} - \cancel{F_{FP}}\cancel{F_{CD}} + F_{FP}F_{CD}F_{LP} \\
&\quad + \cancel{F_{FP}}\cancel{F_{CD}}\cancel{F_{HP}} - F_{FP}F_{CD}F_{LP}F_{HP} + \cancel{F_{CC}} - F_{LP}F_{CC} - \cancel{F_{HP}}\cancel{F_{CC}} \\
&\quad + F_{LP}F_{HP}F_{CC} - \cancel{F_{FP}}\cancel{F_{CC}} + F_{FP}F_{LP}F_{CC} + \cancel{F_{FP}}\cancel{F_{HP}}\cancel{F_{CC}} - F_{FP}F_{LP}F_{HP}F_{CC} \\
&\quad - \cancel{F_{CD}}\cancel{F_{CC}} + F_{CD}F_{LP}F_{CC} + \cancel{F_{CD}}\cancel{F_{HP}}\cancel{F_{CC}} - F_{CD}F_{LP}F_{HP}F_{CC} + \cancel{F_{FP}}\cancel{F_{CD}}\cancel{F_{CC}} \\
&\quad - F_{FP}F_{CD}F_{LP}F_{CC} - \cancel{F_{FP}}\cancel{F_{CD}}\cancel{F_{HP}}\cancel{F_{CC}} + F_{FP}F_{CD}F_{LP}F_{HP}F_{CC}
\end{aligned}$$

$$\begin{aligned}
F_{LP} = (&q_5 - q_5q_9 - q_5q_{11} + q_5q_9q_{11} - q_5q_7 + q_5q_7q_9 + q_5q_7q_{11} - q_5q_7q_9q_{11} - q_5q_{13} + q_5q_9q_{13} \\
&+ q_5q_{11}q_{13} - q_5q_9q_{11}q_{13} + q_5q_7q_{13} - q_5q_7q_9q_{13} - q_5q_7q_{11}q_{13} + q_5q_7q_9q_{11}q_{13})[1-(1-q_6)(1-q_8) \\
&(1-q_{10})(1-q_{12})(1-q_{14})]
\end{aligned}$$

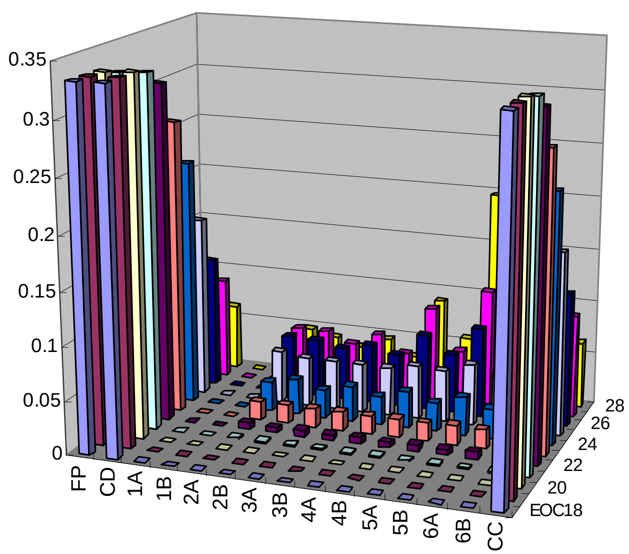
$$\mathrm{FV}(q_5) = \frac{p\left(\bigcup_{i=1}^{15}\mathrm{MCS}_i^{(q_5)}\right)}{R(q)} = 9.84\mathrm{E}-02$$



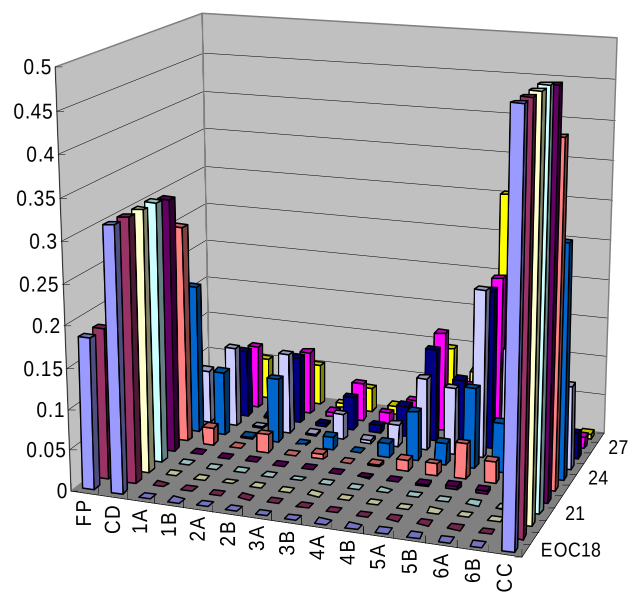
RAW IM



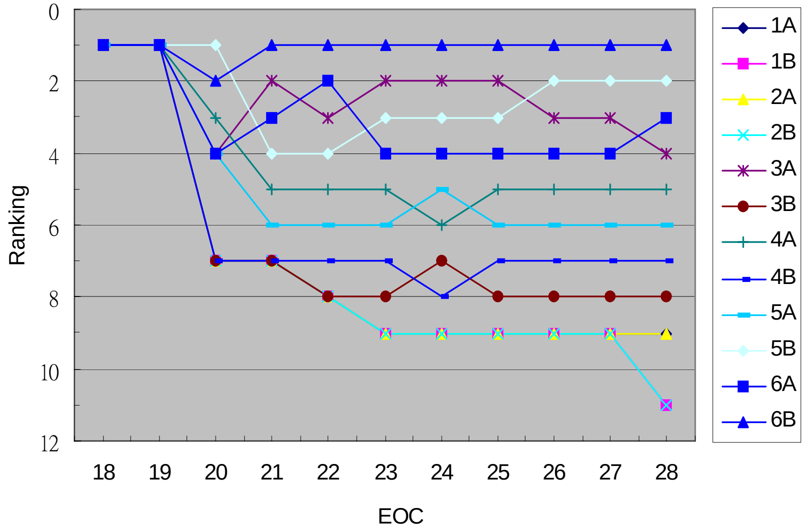
FV IM



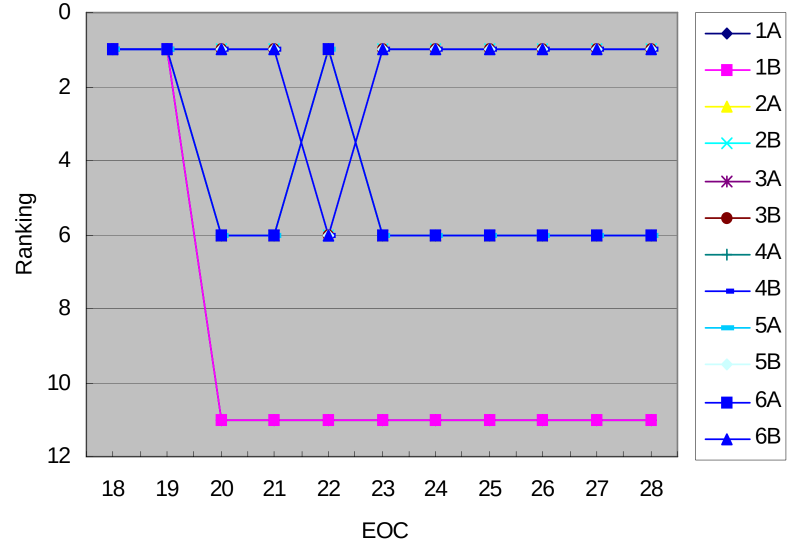
DIM H1



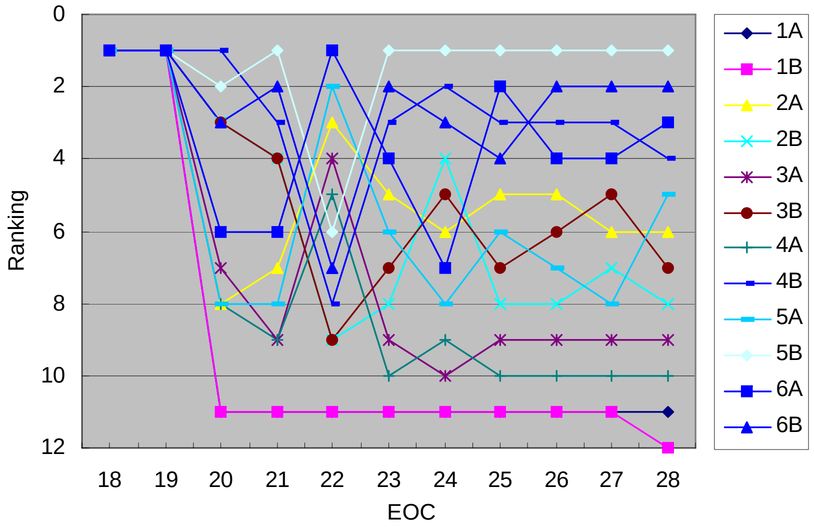
DIM H2



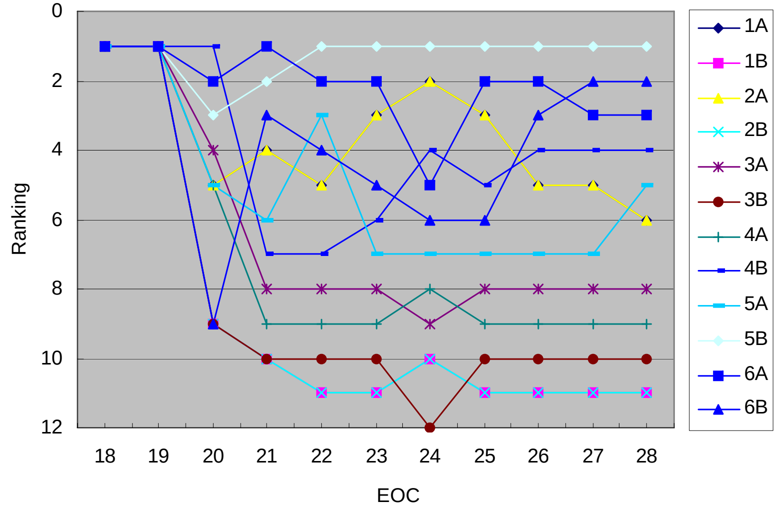
Risk Rank by FV IM



Risk Rank by RAW IM



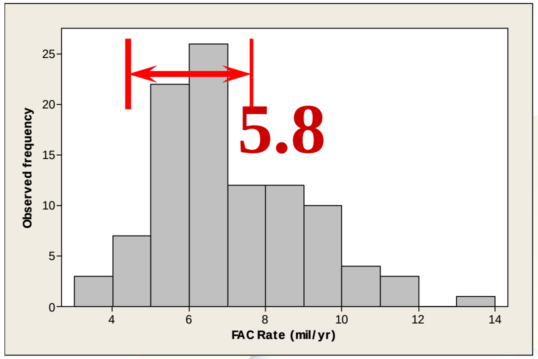
Risk Rank by DIM H1



Risk Rank by DIM H2

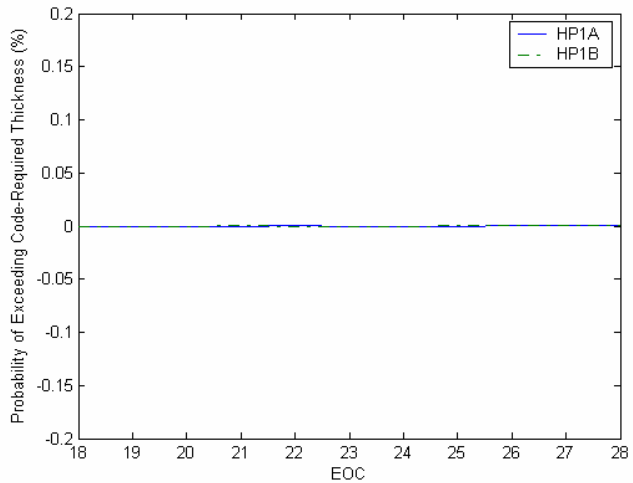
Concluding Remarks

- KWU model predicts FAC of FWH well

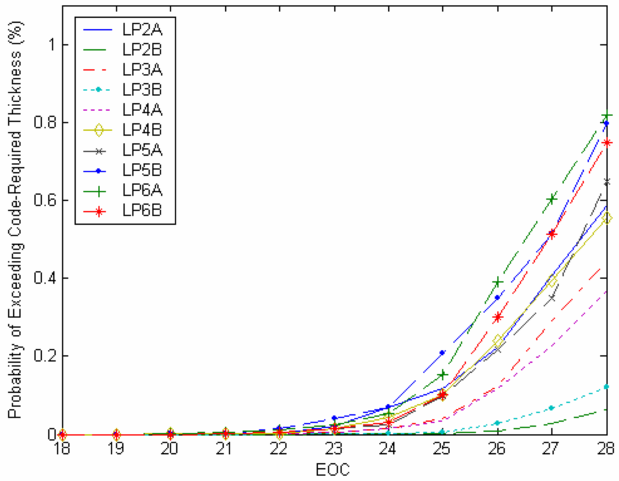


基本資料			
測件名稱	FW-LP3A-L1		
材質	SA-515-70	設計規範	ASME VIII
管徑	63”	設計壓力	250 psi
公稱壁厚	0.542”	設計溫度	405 °F
最小壁厚	0.492”	運轉壓力	
蒸汽乾度	0.88	運轉溫度	
殼側薄化率(mil/yr)			
殼側本體	5.8		

- In studied case, FWHs at high-pressure section have lower risk ranks, and can be allowed for less intensive examination if so desired



- Those deserve more intensive examinations are LP6B、LP6A、LP5A、LP5B、LP4B



- As compared to RAW IM, FV IM & DIM are more effective to distinguish risk differences among components

- Although LP2A & LP3A locate close to high-pressure section, their risks are moderately high (owing to smaller allowable thicknesses) and need to be paid attention to

- The case study indicates a risk-based inspection plain or risk-based management program can be employed to replace the current code-based inspection program

Thank you for your attention.

The above viewpoints do not necessarily reflect those of AEC and NSC of Taiwan.