



# Research progress on operational safety and risk monitoring & prediction of nuclear power plants

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## Risk Monitor(RM)

- PRA uses static failure rates (generic – component class)
- PRA does not rely on current component condition
- Population-based event and probabilities of failure (POF) are used
- Passive component failures are largely excluded from risk monitors (except as initiating events)
- Economic metric is not integral to PRA

## Enhanced Risk Monitor (ERM)

- ✓ real-time assessments of equipment condition
- ✓ predicted probabilities of failure
- ✓ risk monitoring & prediction
- ✓ multi-objective optimization (Safety metric & Economic metric )

# Research background & significance



## Enhanced Risk Monitor (ERM)

- ✓ -Characterize real-time risk of operating with **degraded components** – optimize operation planning and maintenance scheduling
- ✓ – Offset limited advanced reactor component reliability data by providing tools for assessing risk (safety, **economics, regulatory compliance**) when operating with **new component designs**

ERM methodology leverages time-dependent PRA

**PHM** (Prognostics and Health Management ) detects and monitors component health & predicts component failure rates (prognostics)

**PRA** uses these predictive failure rates to estimate

- **Safety metric** (using cutsets leading to core damage)
- **Economic metric** (using cutsets leading to unplanned outage)

**ERM coupled with predictive maintenance is cost-effective for NPPs**

**while maintaining safety goal**



# Research background & significance



$t_0 = 0$ ; Time when component was put in service after test or maintenance

$t_{af}$  = Time of actual failure

$t_m$  = Epoch of time when maintenance / recovery should complete

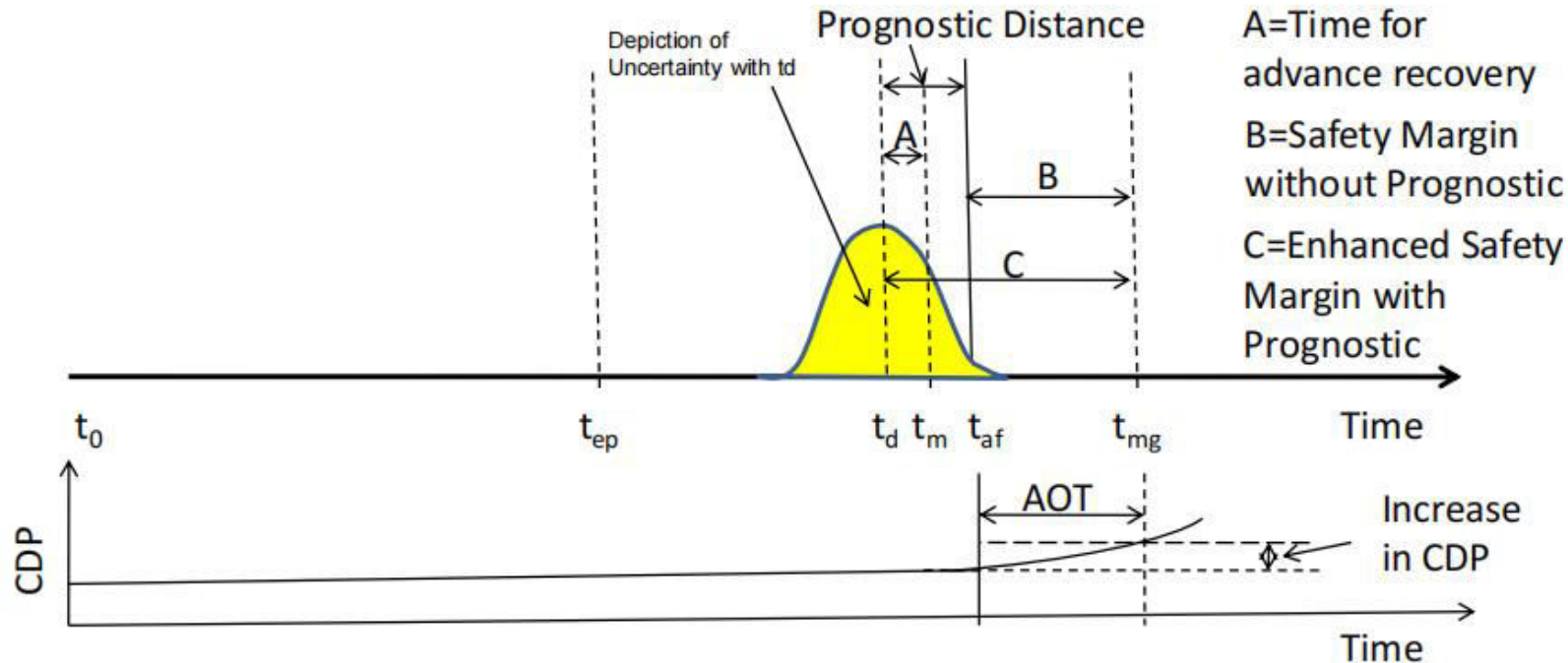
$t_d$  = Prediction of Failure by Prognostic algorithm

$t_{ep}$  = Early prediction of deviation

$t_m - t_d$  = Time required for reconfiguration / recovery action = A

$t_{mg} - t_{af}$  = Time available for repair / recovery / mitigation (referred as plant coping time) = B

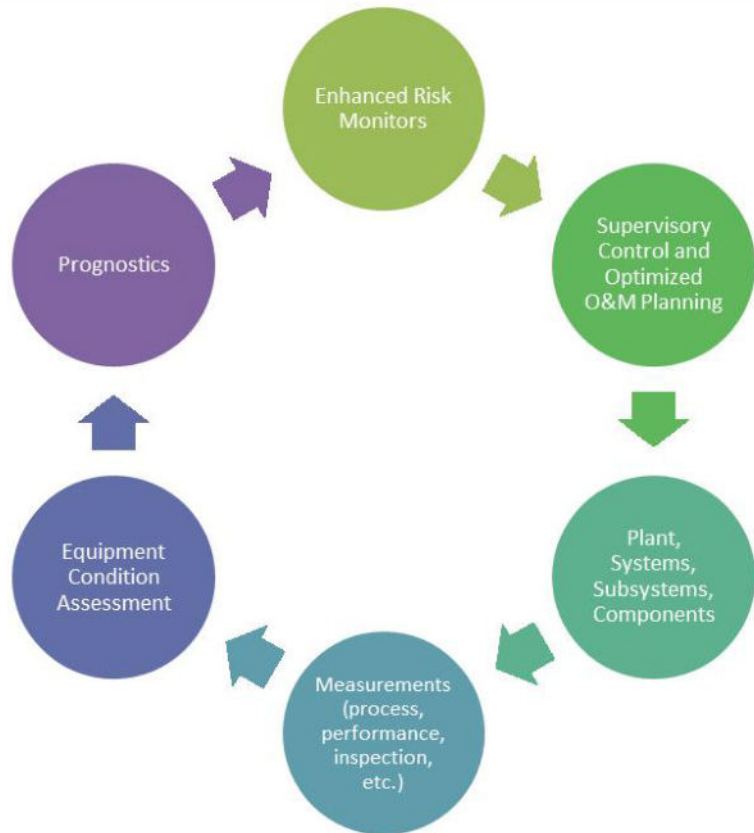
$t_d - t_{mg}$  = Time available for repair / recovery / mitigation (referred as plant coping time) = C



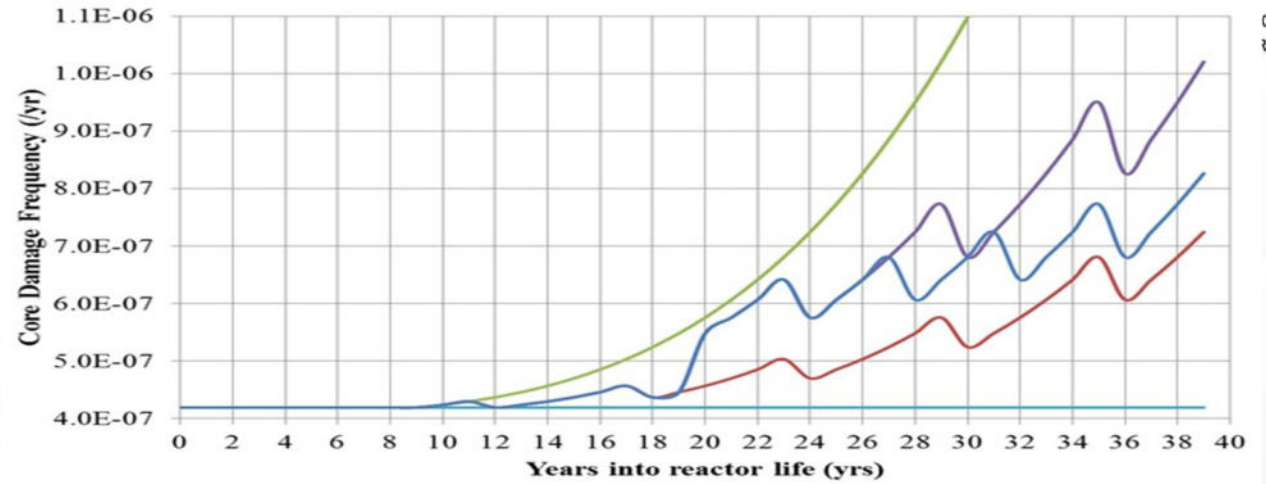
# Research background & significance



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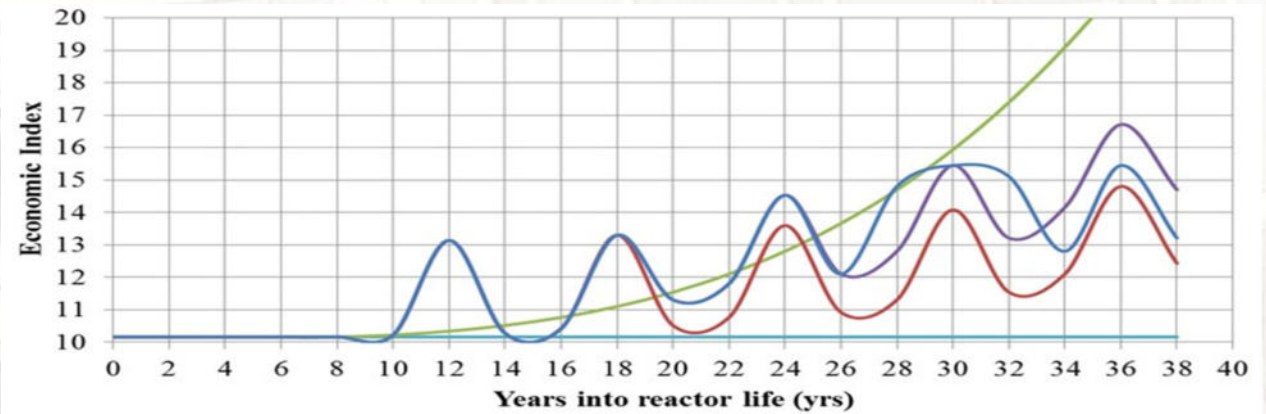


CDF



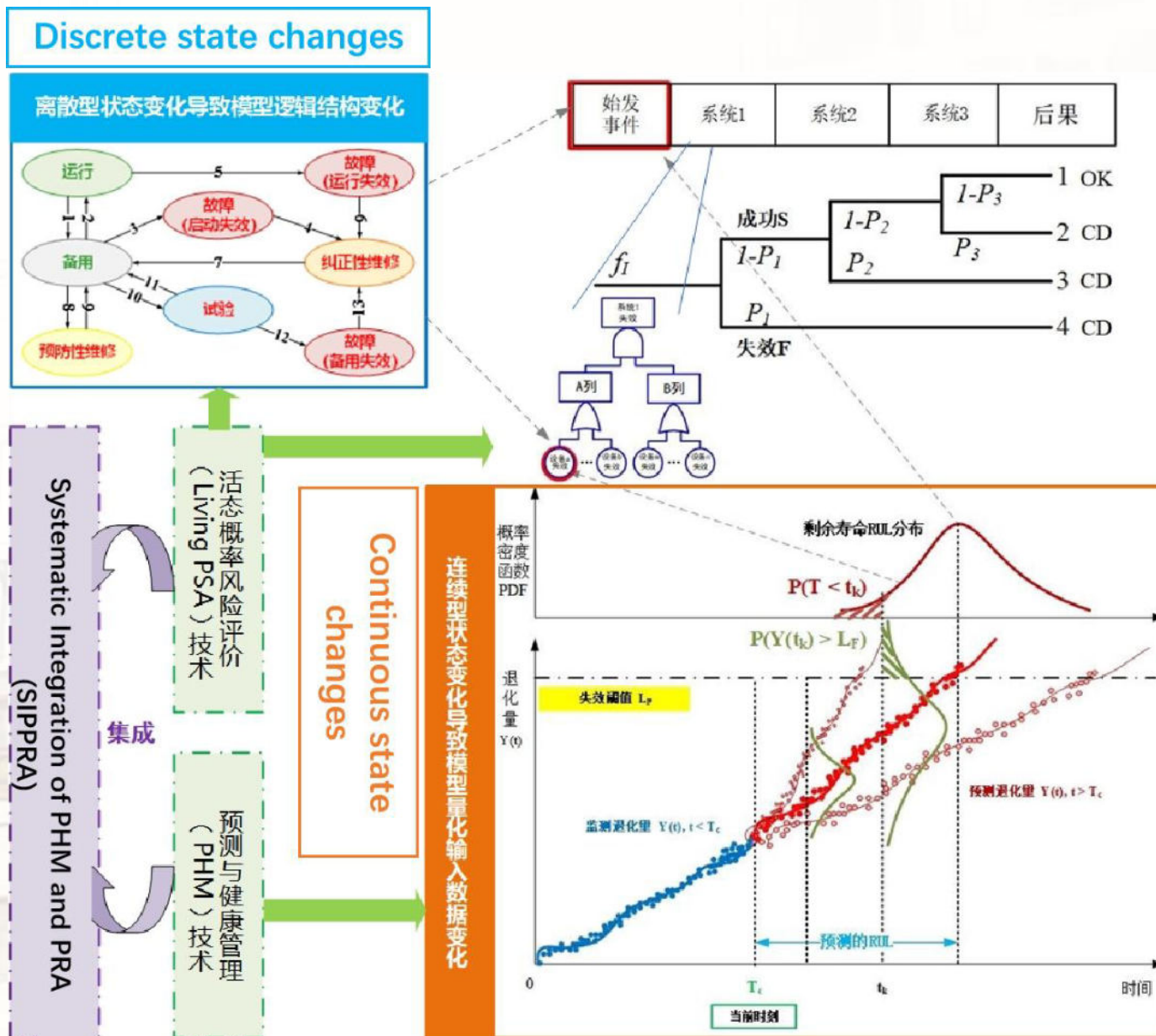
- Decision 0 - No significant aging, Minimal maintenance
- Decision 1 - Aging, No maintenance
- Decision 2 - Aging, Maintenance every six years
- Decision 3a - Accelerated aging around 20 years, Maintenance every six years
- Decision 3b - Accelerated aging around 20 years, Maintenance every four years

Economic Index



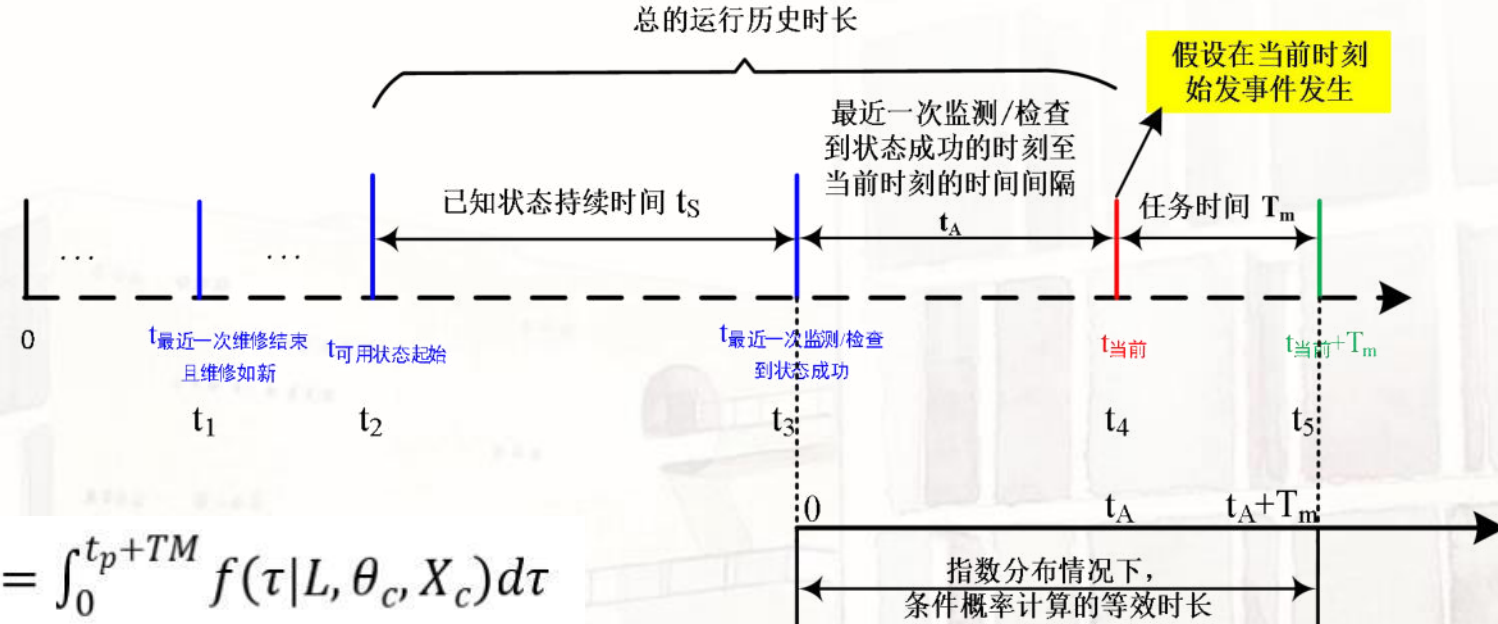
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# Technical roadmap





# Timeline design for risk monitoring/ prediction



$$F(t_c + t_p + TM | t_c) = \int_0^{t_p + TM} f(\tau | L, \theta_c, X_c) d\tau$$

指数分布情况下, 条件概率计算的等效0点

指数分布情况下, 条件概率计算的等效终点





# Timeline design for risk monitoring/ prediction

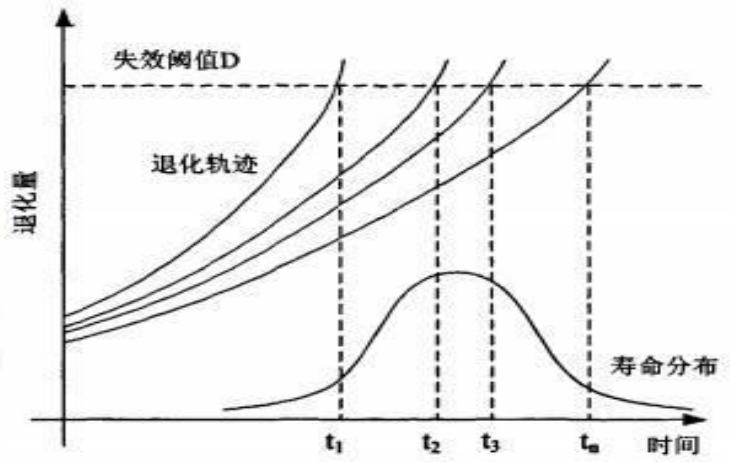
$$RUL = \inf\{t_R: X(t_c + t_R) \geq L\}$$

$$F(t_c + t_p + TM|t_c) = \int_0^{t_p+TM} f(\tau|L, \theta_c, X_c) d\tau$$

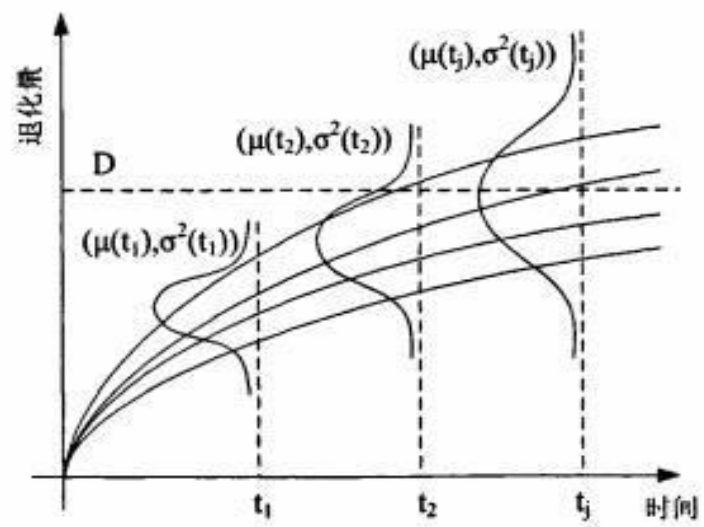
The concept of time-varying probability of failure (POF) based on performance degradation and its predictive theoretical methods

$$F_T(t) \approx P(X_t \geq L) = \int_L^\infty \lambda_{t^*}(X) dx$$

## Fitting the PDF of Remaining Useful Life (RUL)



## Fitting the PDF of the Health Indicator (HI)



The predicted time-varying POF can directly derive the cumulative distribution function (CDF) of the RUL



# The data interface between PHM and RM



## 15 types of data that PHM transmits to PB-RMP in real-time:

- BoxId
- Sampling Time
- Sampling Rate
- Channel Num
- Channel Name
- Channel Status
- Speed RPM
- Speed RPM Status
- Target Equipment
- Target Overall Health
- Failure Mode
- Health Indicator Value
- Health Indicator Alarm Level
- Remaining Useful Life
- Probability Distrib Func

## 3 types of human-machine interaction data:

- Time period for prediction
- Time step for prediction
- Integration accuracy

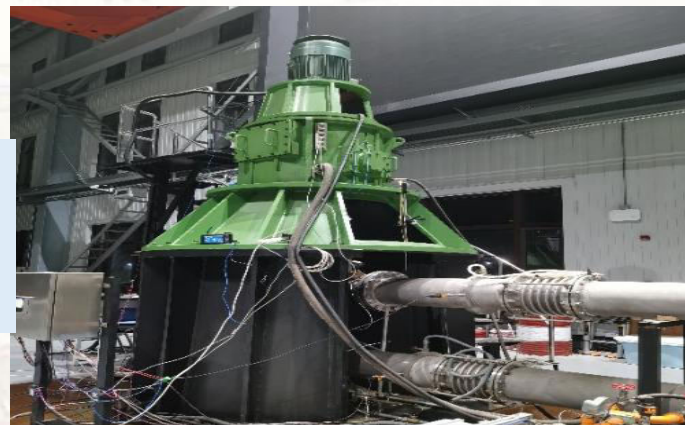


# Accumulated full lifecycle data of the circulating water pump

Fault experiments for over a year and lifecycle experiments for six months have been conducted on the circulating water pump, accumulating a large amount of data.



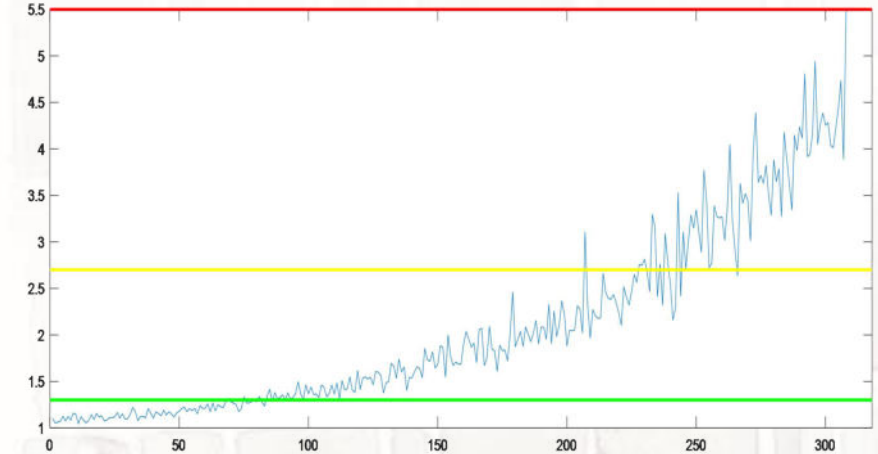
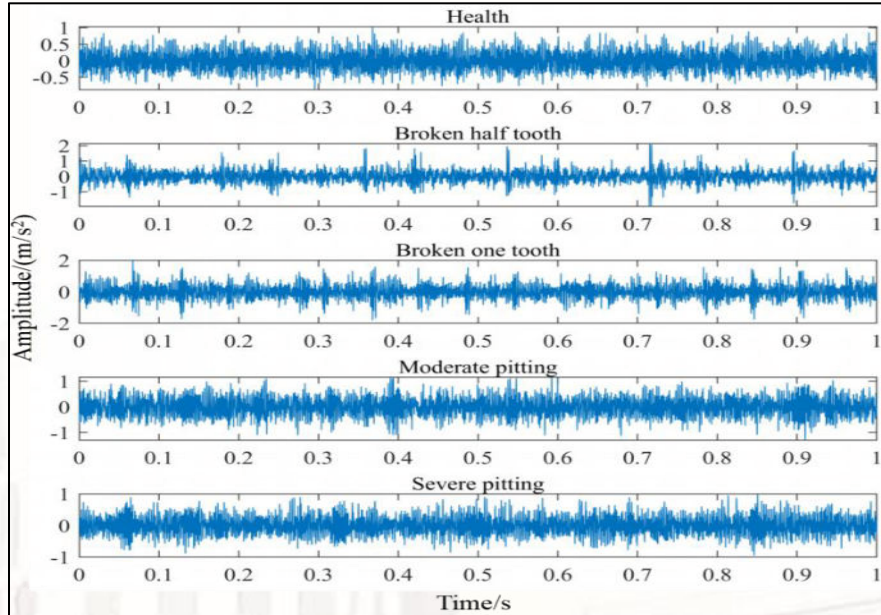
On-site data collection and data collection terminal



Accumulated multiple sets of fault data and full life data



# The health indicators for the full lifecycle of the circulating water pump obtained from the experimental study



The entire dataset consists of 308 days of data, representing the full lifecycle of a circulating water pump from a healthy state to a shutdown for maintenance. In this study, the data has been scaled down. The data is arranged in chronological order, with the amplitudes gradually increasing. The green, yellow, and red lines represent thresholds for different levels of health conditions.

According to the study, the amplitude was selected as the health indicator for the pump. The original amplitude data was collected under different health conditions and fault modes. After processing and calculation, a dataset of 308 days was obtained.

## The change trend of the health indicators for the full lifecycle of the circulating water pump



# Fit Exponential Degradation Models for Remaining Useful Life



## (RUL) Estimation

Fit Exponential Degradation Models for Remaining Useful Life (RUL) Estimation  
Exponential degradation model is defined as

$$h(t) = \phi + \theta \exp\left(\beta t + \epsilon - \frac{\sigma^2}{2}\right)$$

where

- $h(t)$  is the health indicator as a function of time.
- $\phi$  is the intercept term considered as a constant.
- $\theta$  and  $\beta$  are random parameters determining the slope of the model,
  - $\theta$  is lognormal-distributed
  - $\beta$  is Gaussian-distributed.
  - At each time step  $t$ , the distribution of  $\theta$  and  $\beta$  is updated to the posterior based on the latest observation of  $h(t)$ .
- $\epsilon$  is a Gaussian white noise yielding to  $N(0, \sigma^2)$ .
- The  $-\sigma^2/2$  term in the exponential is to make the expectation of  $h(t)$  satisfy

$$E[h(t)|\theta, \beta] = \phi + \theta \exp(\beta t)$$

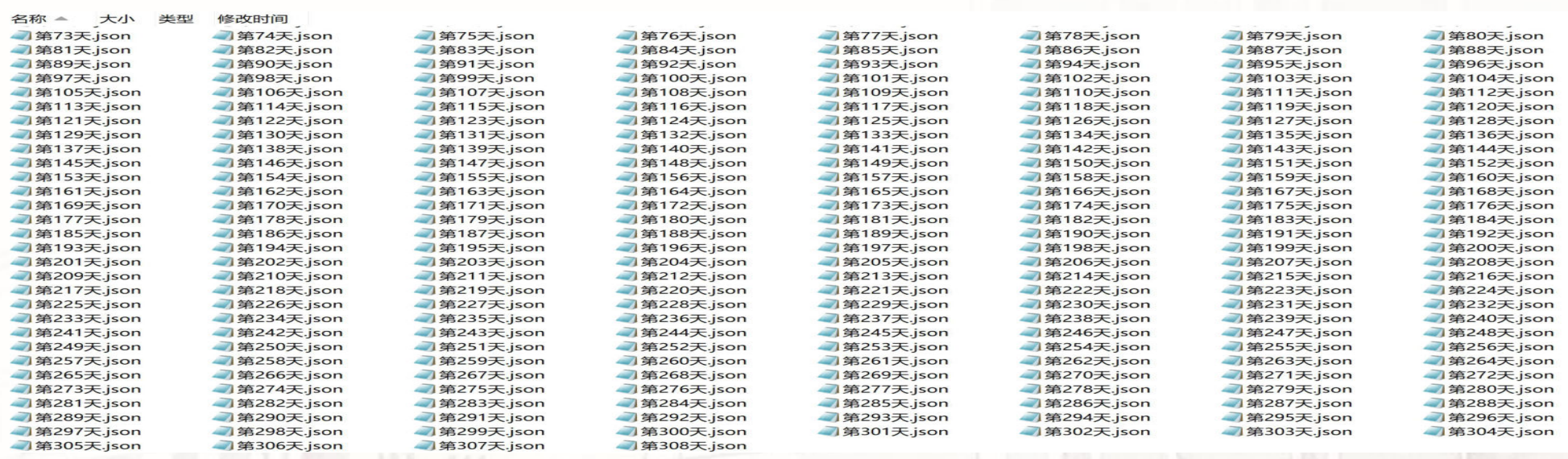




# Fit Exponential Degradation Models for Remaining Useful Life

## (RUL) Estimation

The data of 308 days have been saved as 308 folders, with each folder containing the data information of one day:



### Data information of a specific day:

```
第194天.json - 记事本
文件(F) 编辑(E) 格式(O) 查看(V) 帮助(H)
["Status": "true", "ErrorMessage": "NULL", "BoxId": "AB30AA04", "SamplingTime": "03-Jul-2023 13:06:44", "SamplingRate": 10240, "ChannelNum": 1, "ChannelName": "齿轮箱振动", "ChannelStatus": "正常", "SpeedRPM": 1920, "SpeedRPMStatus": "正常", "TargetEquipment": "循环水泵", "TargetOverallHealth": "健康", "FailureMode": "劣化", "HealthIndicatorValue": 1.2810348032669805, "HealthIndicatorAlarmLevel": 0, "RemainingUsefulLife": 91.669576475797868, "ProbabilityDistribFuncX": [0.21229004363706849, 1.21731516926552091, 2.2223402948933497, 3.2273654205214908, 4.2323905461496309, 5.2374156717777725, 6.2424407974059131, 7.2474659230340537, 8.2524910486621934, 9.257516174290334, 10.262541299918476, 11.267566425546617, 12.272591551174758, 13.277616676802898, 14.282641802431039, 15.287666928059179, 16.292692053687318, 17.297717179315459, 18.3027423049436, 19.30776743057174, 20.312792556199884, 21.317817681828025, 22.322842807456166, 23.327867933084306, 24.332893058712447, 25.337918184340587, 26.342943309968728, 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# Calculate the POF based on the PDF for RUL



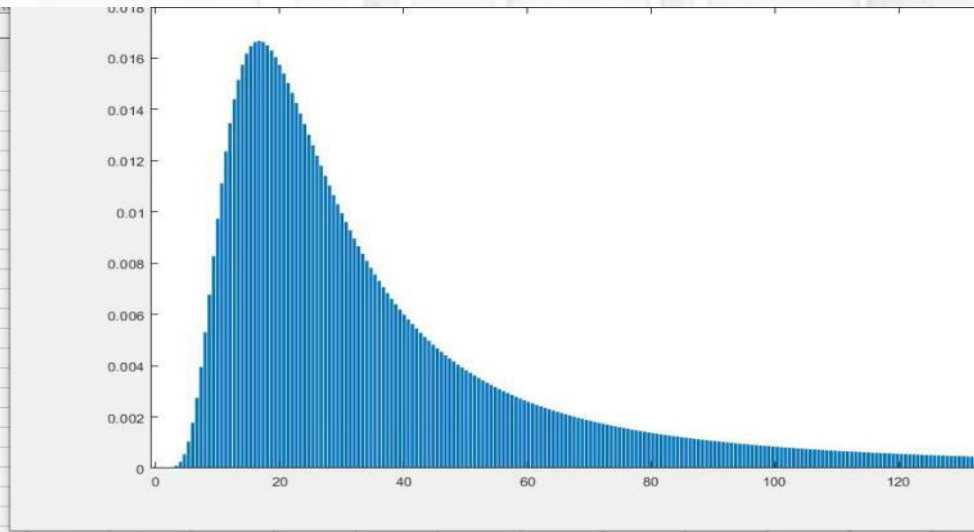
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第7天.json
D:\> 数据文件-报告-使用说明 > 3、实时传输原始数据 > {} 第7天.json > SpeedRPMStatus
15 "HealthIndicatorValue": 1.1247797337533028,
16 "HealthIndicatorAlarmLevel": 0,
17 "RemainingUsefulLife": 18.040790535671089,
18 "ProbabilityDistribFuncX": [
19   0,
20   0.60135968452236965,
21   1.2027193690447393,
22   1.8040790535671092,
23   2.4054387380894786,
24   3.0067984226118485,
25   3.6081581071342184,
26   4.2095177916565873,
27   4.8108774761789572,
28   5.4122371607013271,
29   6.013596845223697,
```

```
第7天.json
D:\> 数据文件-报告-使用说明 > 3、实时传输原始数据 > {} 第7天.json >
218 119.67057721995157
219 ],
220 "ProbabilityDistribFuncY": [
221   2.8179012493510835E-15,
222   1.1398140805856439E-13,
223   5.07924154214605E-12,
224   1.3460491326949055E-10,
225   2.267815208471353E-9,
226   2.581275597791651E-8,
227   2.0946156098141747E-7,
228   1.269795590060598E-6,
```

The X-axis of the PDF of RUL obtained from calculations

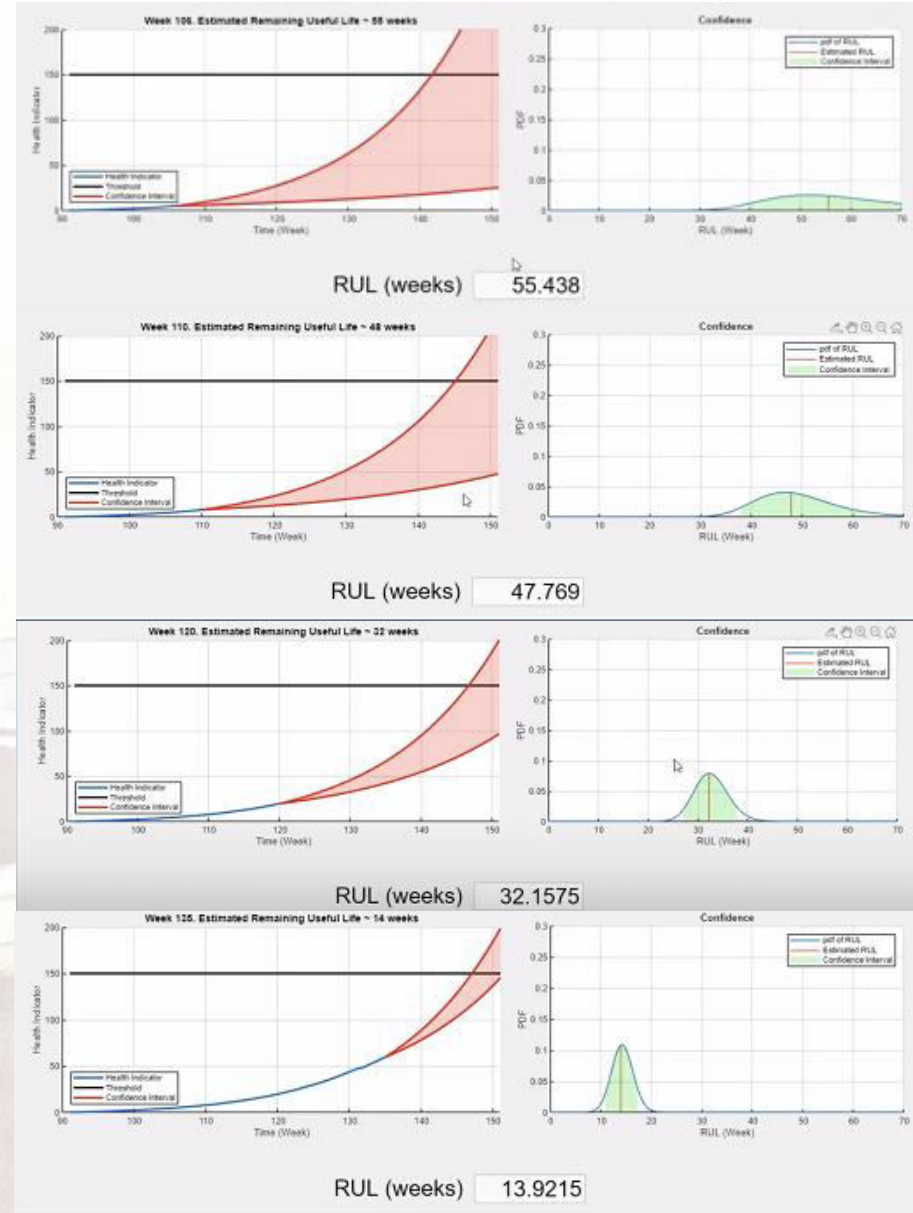
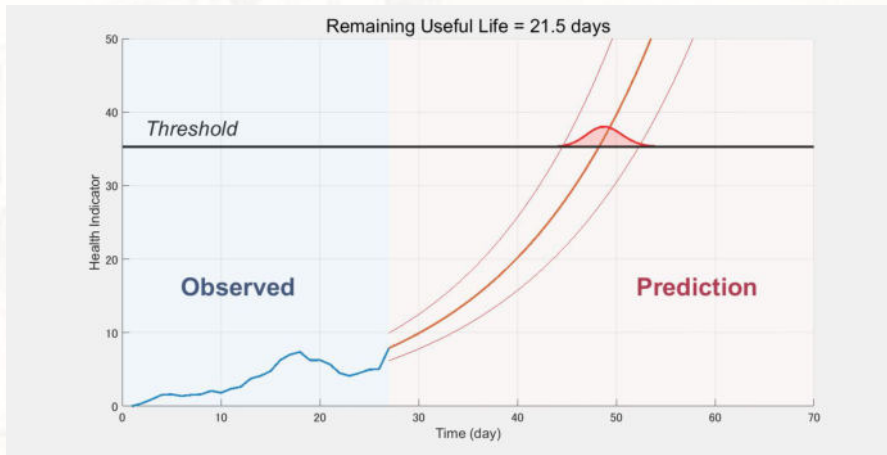
The Y-axis of the PDF of RUL obtained from calculations

	1	2	3	4	5	6	7
	RUL	ProbabilityDensity					
1	0	2.3020e-08					
2	0.6688	1.5585e-07					
3	1.3377	1.2784e-06					
4	2.0065	7.1950e-06					
5	2.6753	2.9725e-05					
6	3.3442	9.5308e-05					
7	4.0130	2.4826e-04					
8	4.6818	5.4537e-04					
9	5.3507	0.0010					
10	6.0195	0.0018					
11	6.6883	0.0028					
12	7.3572	0.0039					
13	8.0260	0.0053					
14	8.6948	0.0068					
15	9.3637	0.0083					
16	10.0325	0.0097					
17	10.7014	0.0111					
18	11.3702	0.0124					
19	12.0390	0.0135					
20	12.7079	0.0144					
21	13.3767	0.0152					
22	14.0455	0.0157					
23	14.7144	0.0162					





# Calculate the POF based on the PDF for RUL

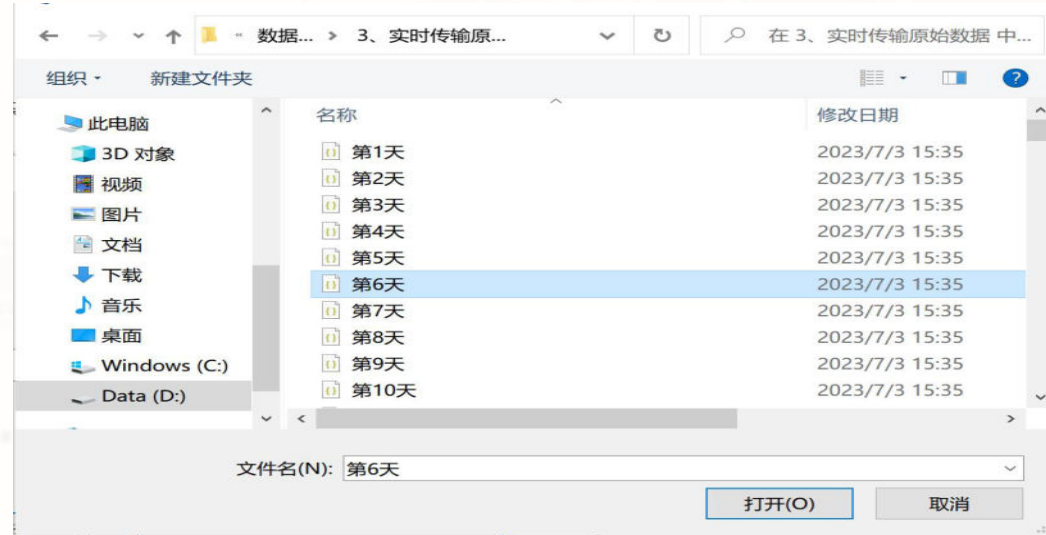


# Calculate the POF based on the PDF for RUL

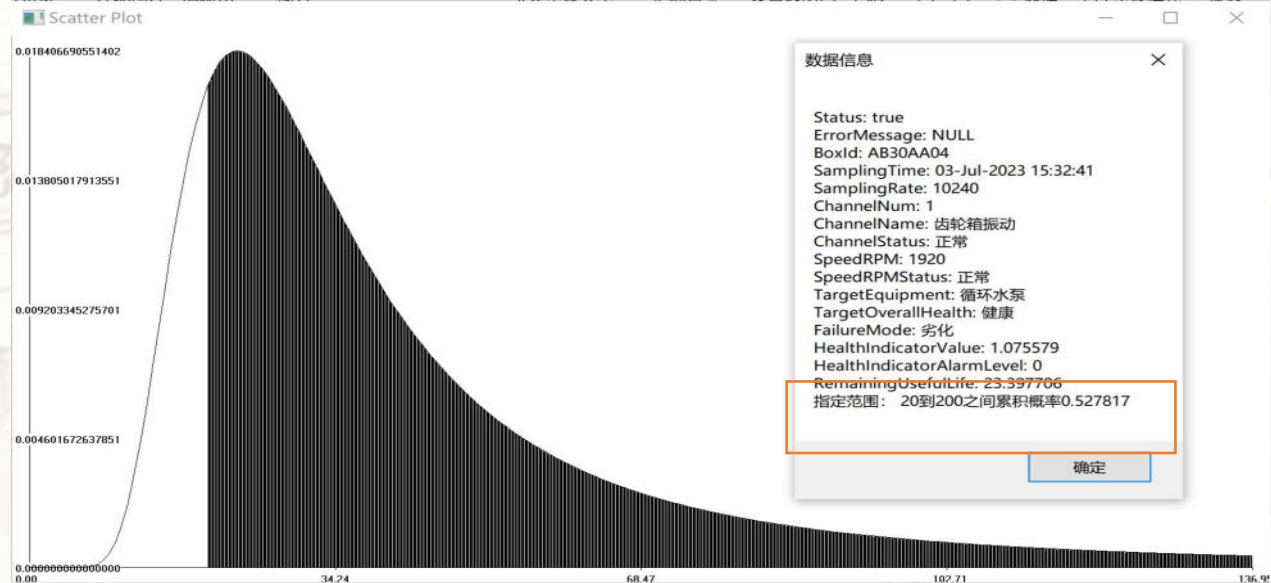


起始天数  终止天数  积分精度

选择实时传输的json数据文件并计算cdf



Calculate the failure probability within a specific time period by setting the time period and integration accuracy



# Calculate the POF based on the PDF for RUL



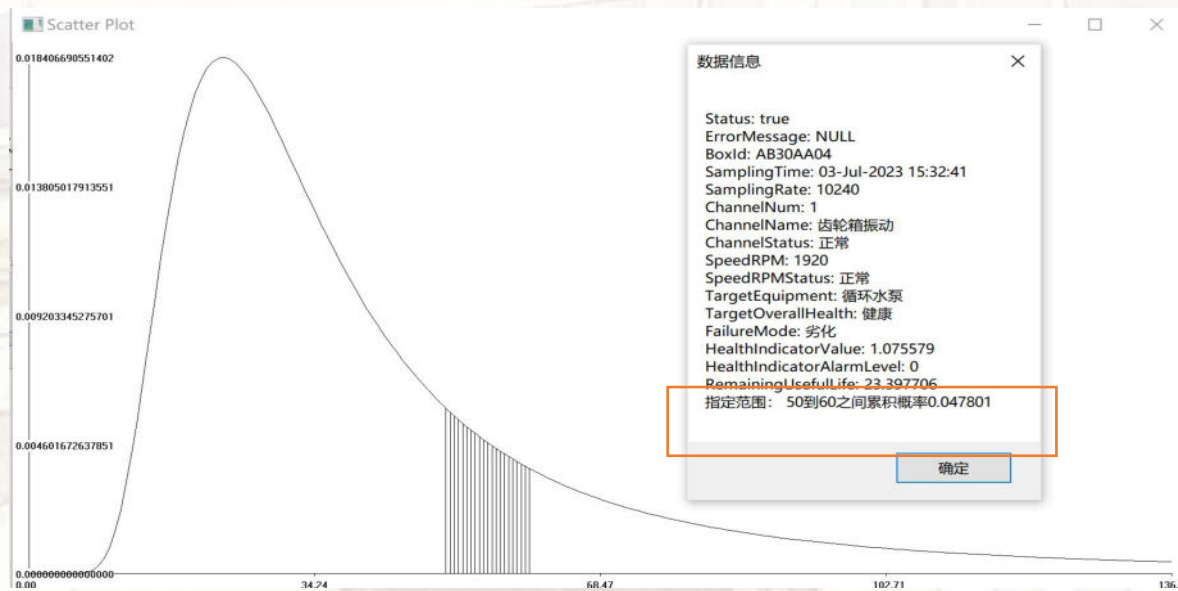
起始天数  终止天数  积分精度

选择实时传输的json数据文件并计算cdf

名称	修改日期
第1天	2023/7/3 15:35
第2天	2023/7/3 15:35
第3天	2023/7/3 15:35
第4天	2023/7/3 15:35
第5天	2023/7/3 15:35
第6天	2023/7/3 15:35
第7天	2023/7/3 15:35
第8天	2023/7/3 15:35
第9天	2023/7/3 15:35
第10天	2023/7/3 15:35

文件名(N): 第6天

打开(O) 取消

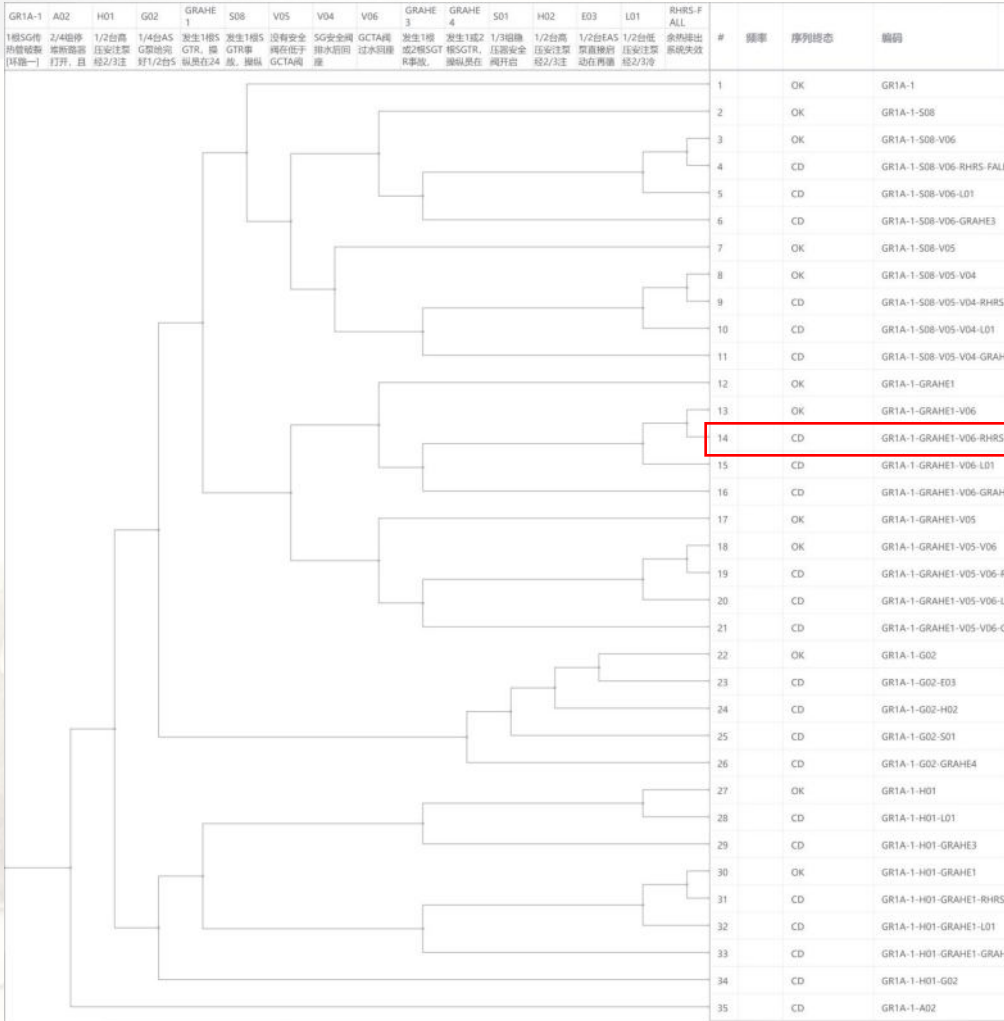




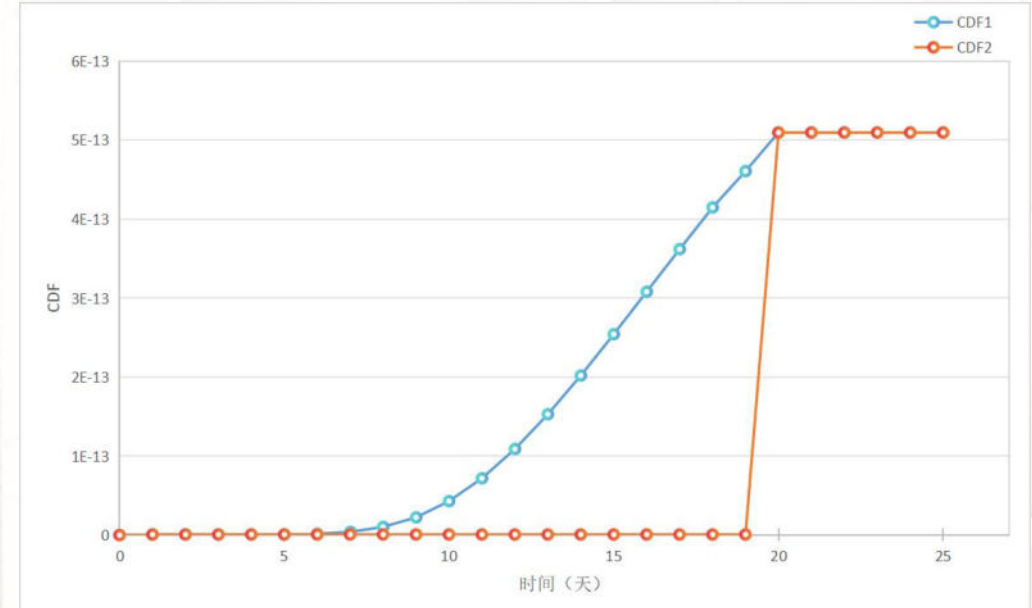
# Case study on Core Damage Frequency (CDF)



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时间 (天)	CDF1	CDF2
0	0	0
1	7.17E-16	7.17E-16
2	7.17E-16	7.17E-16
3	7.17E-16	7.17E-16
4	7.27E-16	7.17E-16
5	8.59E-16	7.17E-16
6	1.55E-15	7.17E-16
7	4.03E-15	7.17E-16
8	1.03E-14	7.17E-16
9	2.23E-14	7.17E-16
10	4.30E-14	7.17E-16
11	7.19E-14	7.17E-16
12	1.09E-13	7.17E-16
13	1.53E-13	7.17E-16
14	2.02E-13	7.17E-16
15	2.54E-13	7.17E-16
16	3.08E-13	7.17E-16
17	3.62E-13	7.17E-16
18	4.15E-13	7.17E-16
19	4.61E-13	7.17E-16
20	5.10E-13	5.10E-13
21	5.10E-13	5.10E-13
22	5.10E-13	5.10E-13
23	5.10E-13	5.10E-13
24	5.10E-13	5.10E-13
25	5.10E-13	5.10E-13



The sequence for case analysis:  
GR1A-1 - GRAHE1 - V06 - RHRS-FALL

CDF with considering the degradation effect (the blue line)  
Vs.  
CDF without considering the degradation effect (the orange line)



# Preventive, corrective maintenance and overhaul effects on component POF

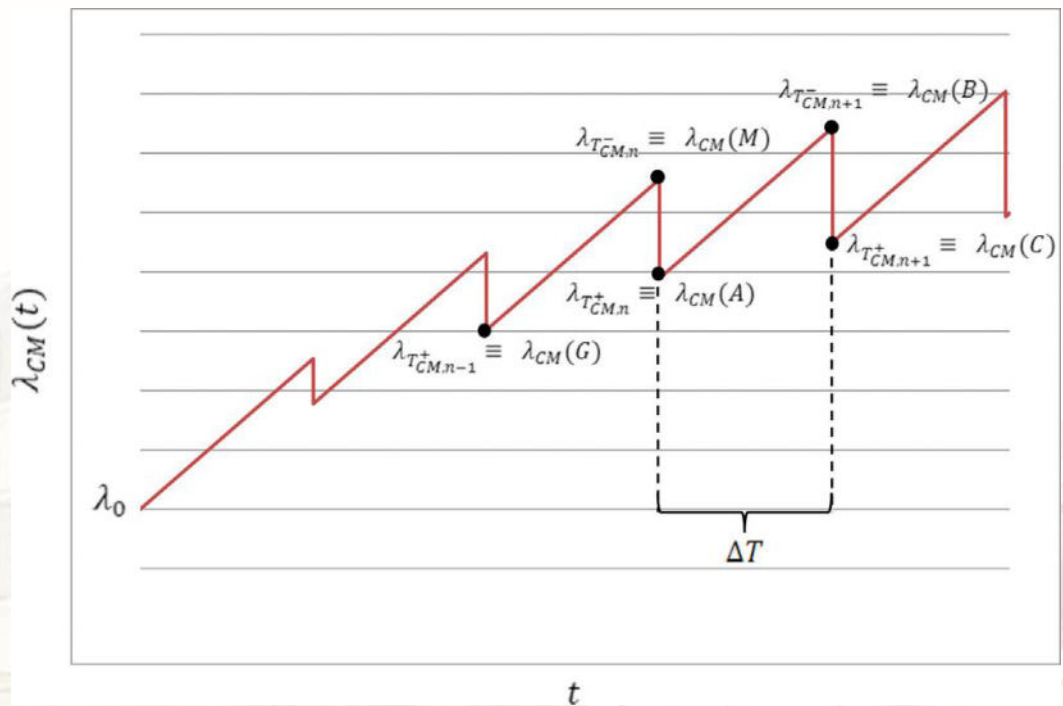


Illustration of  $\lambda_{CM}(t)$

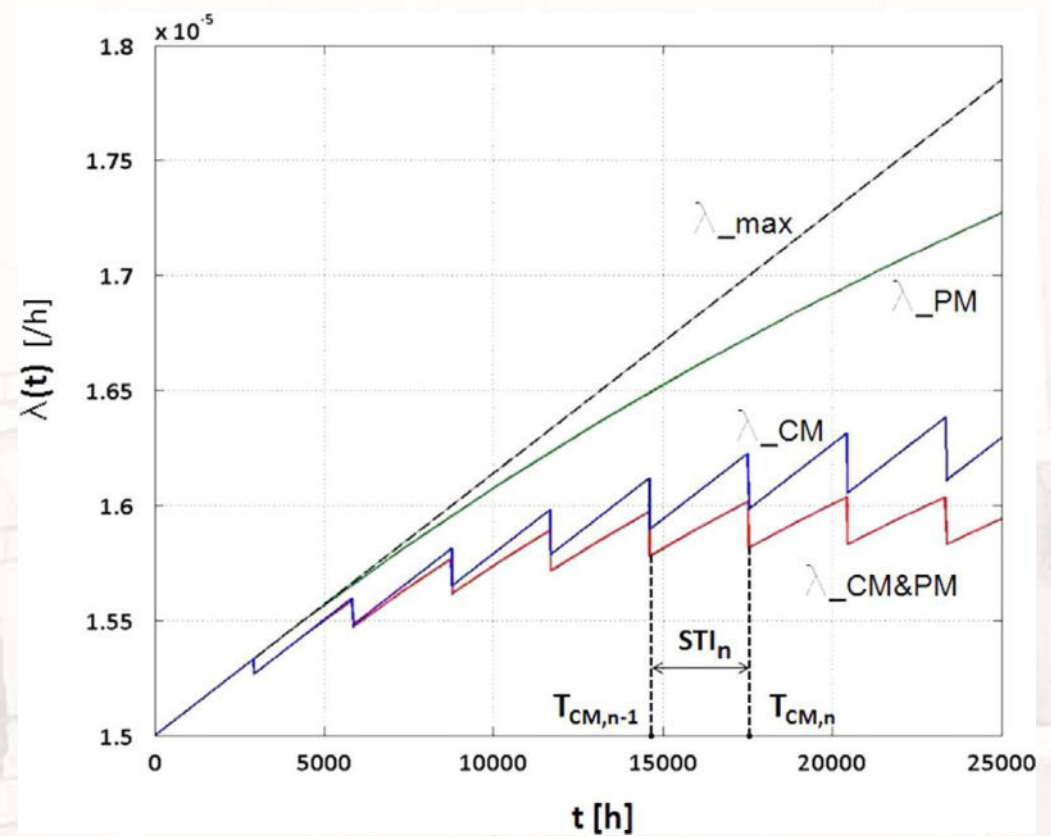


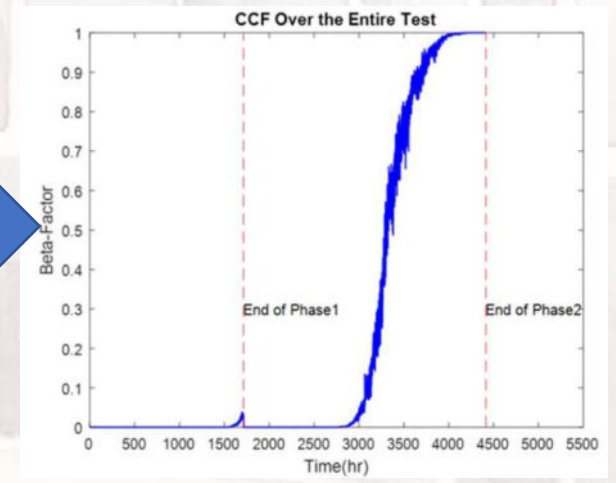
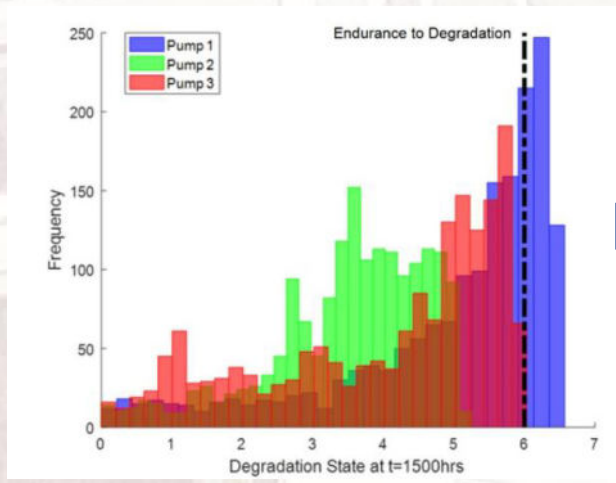
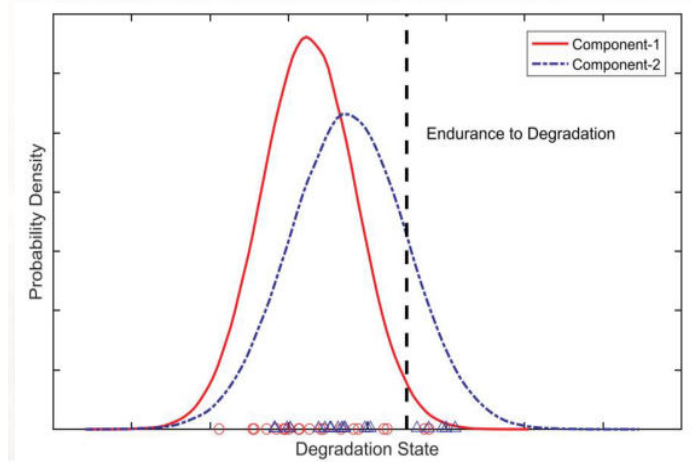
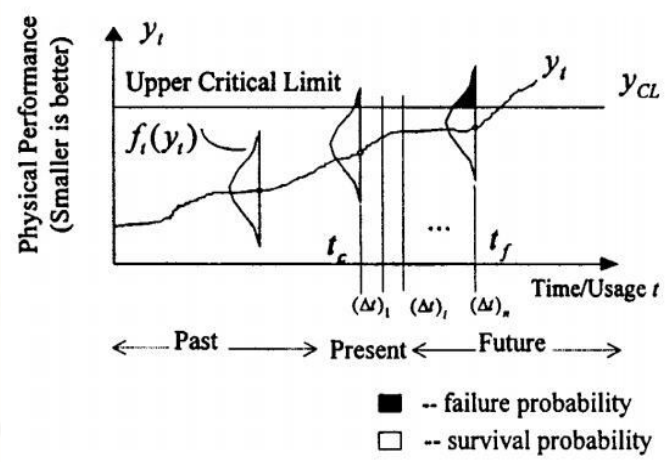
Illustration of the PM, CM and their combined effect on  $\lambda(t)$



# New CCF model for components under the degradation

- Given that the degradation state estimate is known at each time instant, the occurrence of CCF would be indicated by the concurrent exceedance of the endurance to degradation.
- Therefore, the CCF impacts would be characterized by the fraction of multiple exceedances of the endurance to degradation, which follows the conventional parametric CCF model.
- The scope of the parametric CCF model would be extended to be dynamic over the service lifetime rather than being static.

- At each time step, all samples from each component will be collected to describe the degradation state of each component.
- Taking a two-component common cause failure group (CCFG) as an example, the  $\beta(t)$ -factor CCF model is adopted for demonstration, where the  $\beta(t)$  is defined as the proportion of common cause failures at the time  $t$  involving multiple components.
- Specifically, the  $\beta(t)$ -factor at each time instance  $t_k$  is estimated as the ratio of common cause failures involving multiple components.





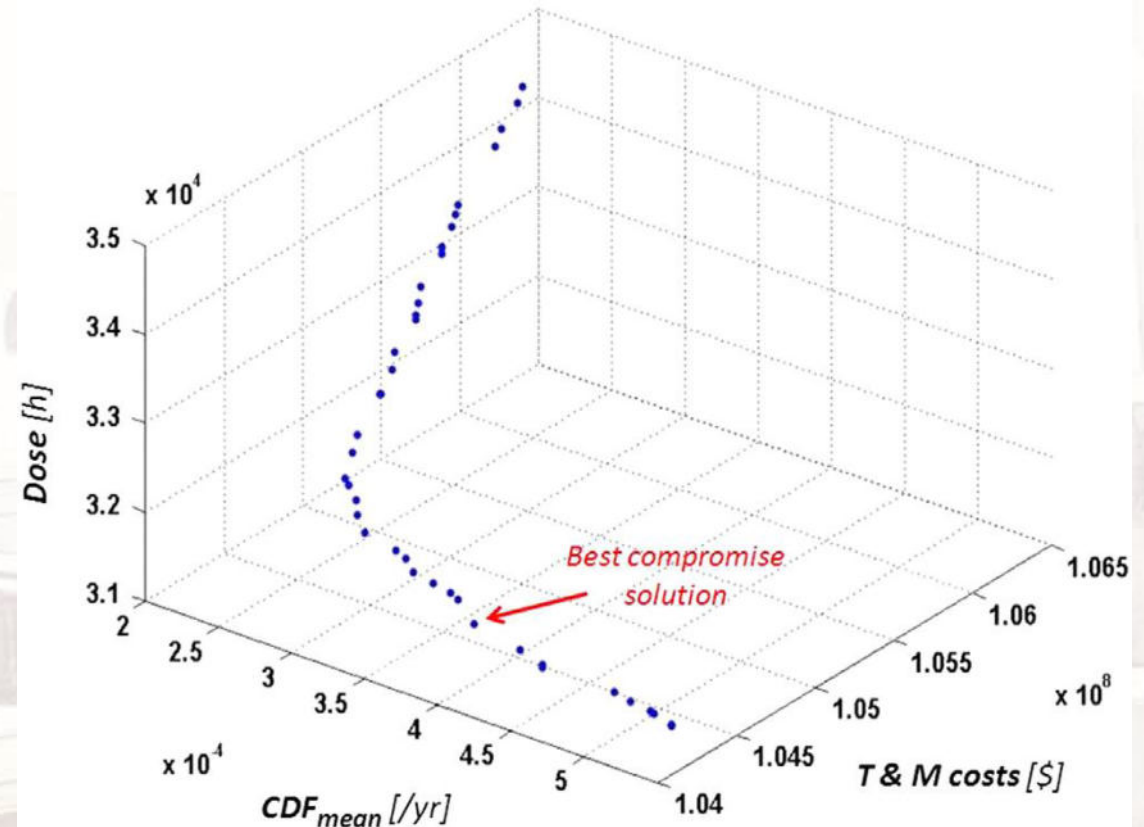
# Plant-level multi-objective optimization



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The multi-objective multi-dimensional optimization problem:

- The mean of CDF(t)
- the total T&M costs
- the exposure time due to performing the T&M activities

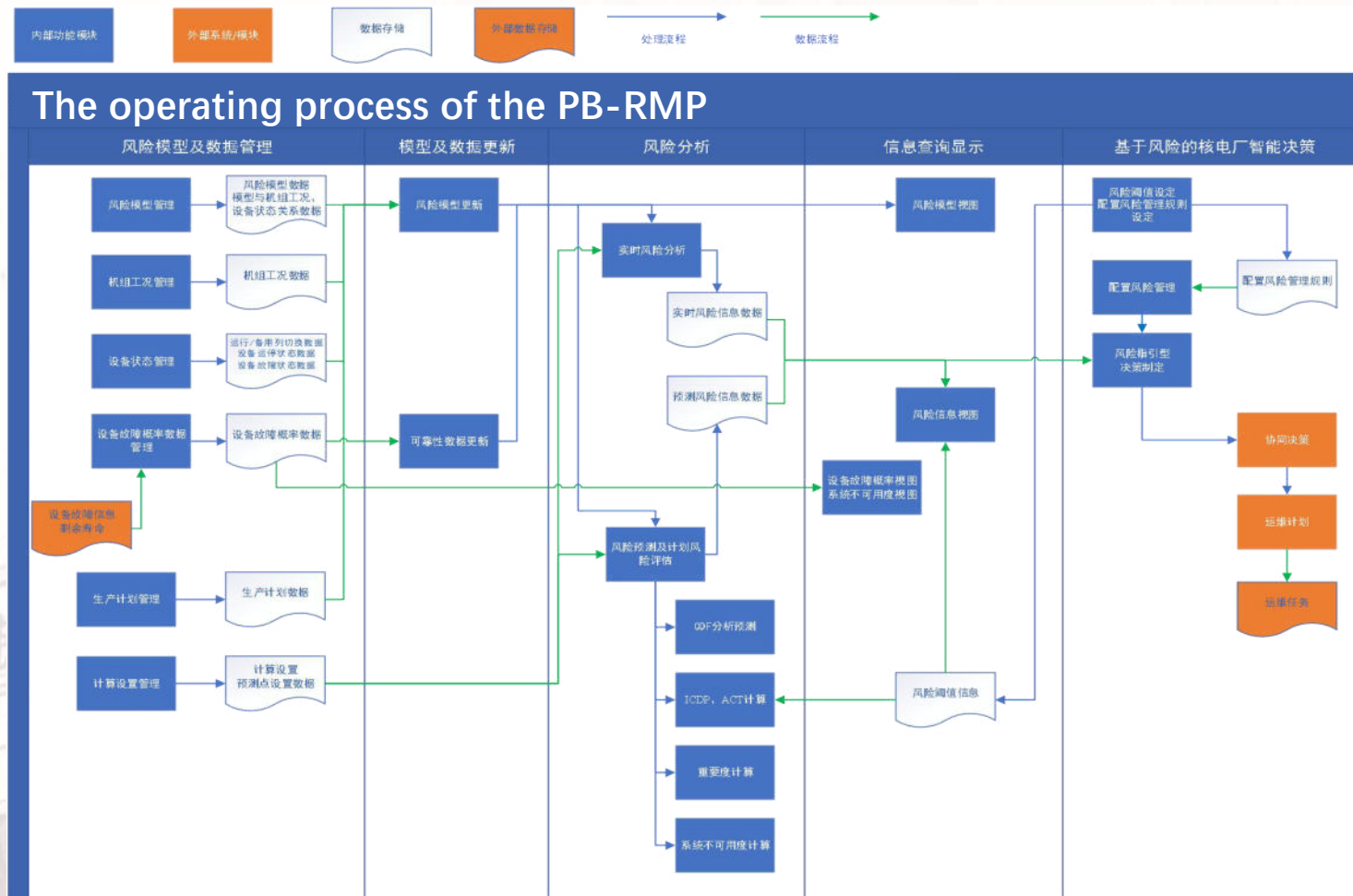
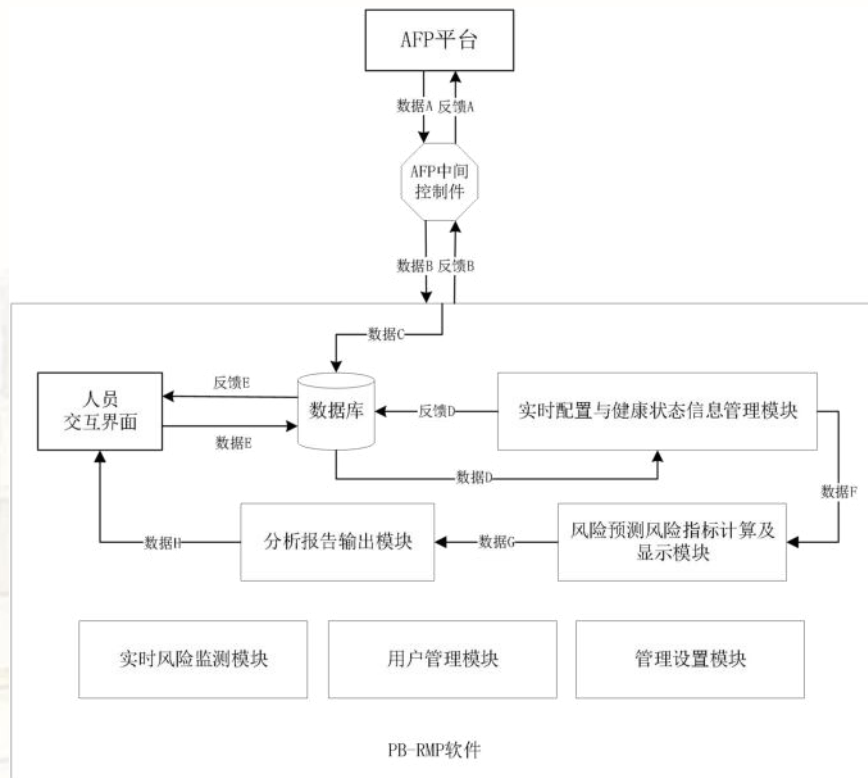


Pareto set of optimal solutions



# Performance-based Risk Monitoring and Prediction (PB-RMP) Software for NPPs

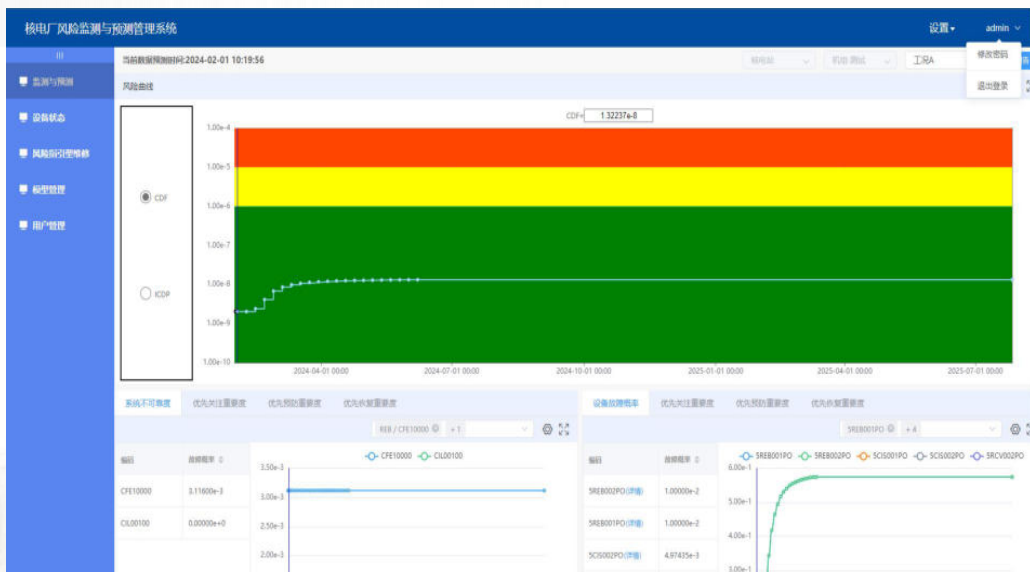
The data architecture of the PB-RMP



# The user interfaces of the PB-RMP



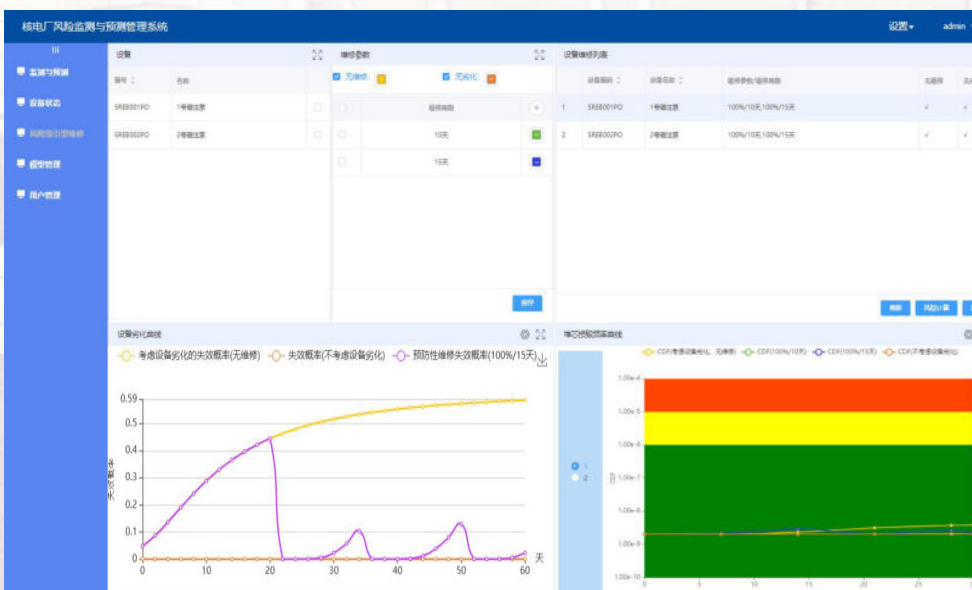
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核电厂风险监测与预测管理系统

名称	名称	设备名称	设备状态	设备状态更新时间
SCAM001VA	安全壳大气监测系统	大门关闭	正常	2024-03-21 16:44:59
SCAM002VA	安全壳大气监测系统	大门关闭	正常	2024-03-21 16:44:59
SCAM003VA	安全壳大气监测系统	大门关闭	正常	2024-03-21 16:44:59
SCAM004VA	安全壳大气监测系统	大门关闭	正常	2024-03-21 16:44:59
SCAM005VA	安全壳大气监测系统	大门关闭	正常	2024-03-21 16:44:59
SCAM006VA	安全壳大气监测系统	大门关闭	正常	2024-03-21 16:44:59
SCAM007VA	安全壳大气监测系统	大门关闭	正常	2024-03-21 16:44:59
SCAM008VA	安全壳大气监测系统	大门关闭	正常	2024-03-21 16:44:59
SCAM009VA	安全壳大气监测系统	大门关闭	正常	2024-03-21 16:44:59
SCAM010VA	安全壳大气监测系统	大门关闭	正常	2024-03-21 16:44:59

设备名称	设备名称	设备名称	设备名称
SCAM011MP	安全壳大气压力/氢气压力传感器	运行	2024-03-21 16:44:59







**Thanks for your attention!**



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