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

Lecturer : Sijuan Chen

Shenzhen University

March 27, 2024

Research background & significance

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

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY

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

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY

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

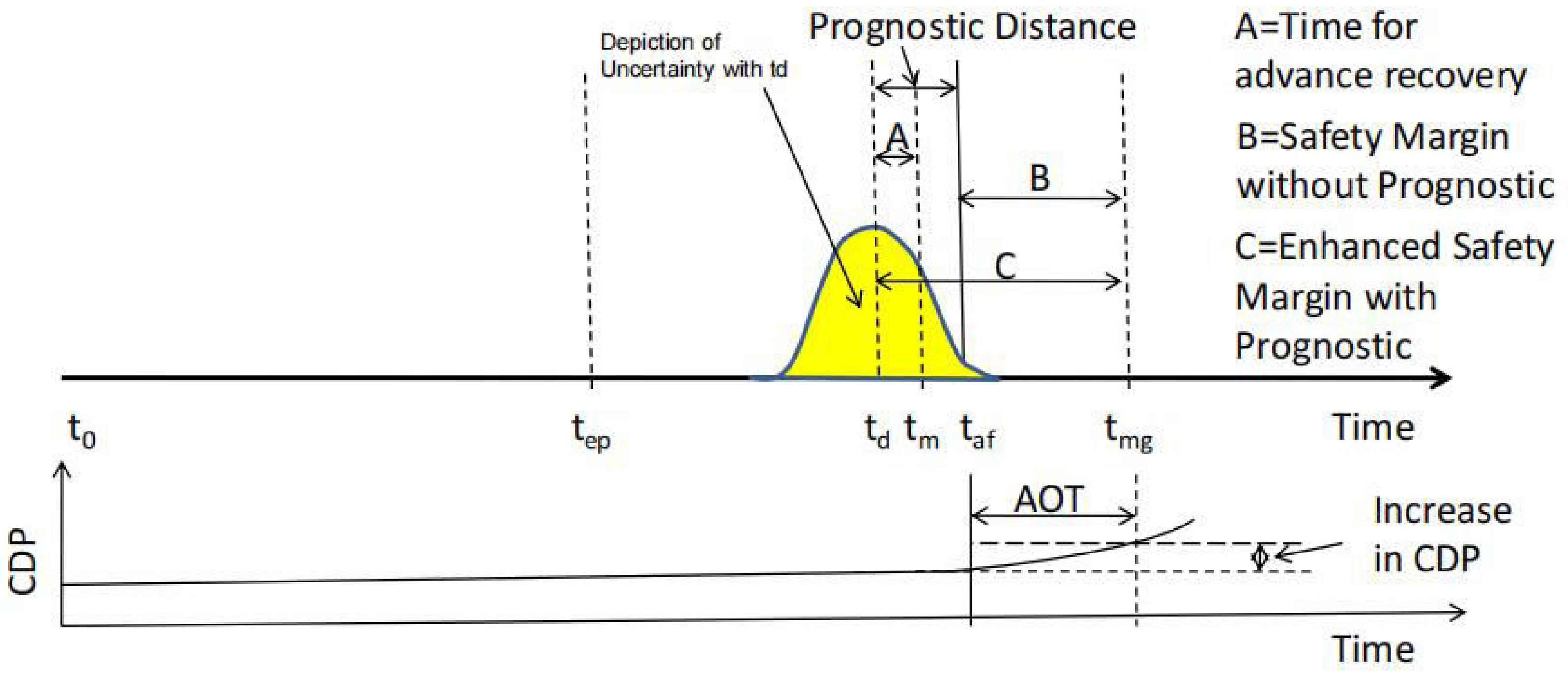
t_d= Prediction of Failure by Prognostic algorithm

t_{ep}= Early prediction of deviation

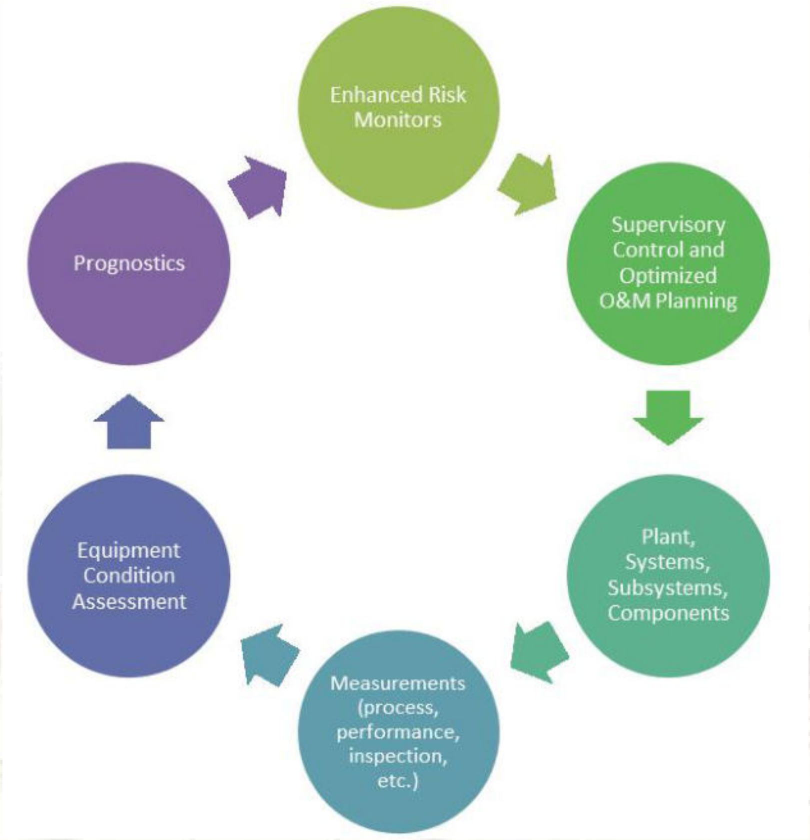
t_m - t_d= Time required for reconfiguration / recovery action = A

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

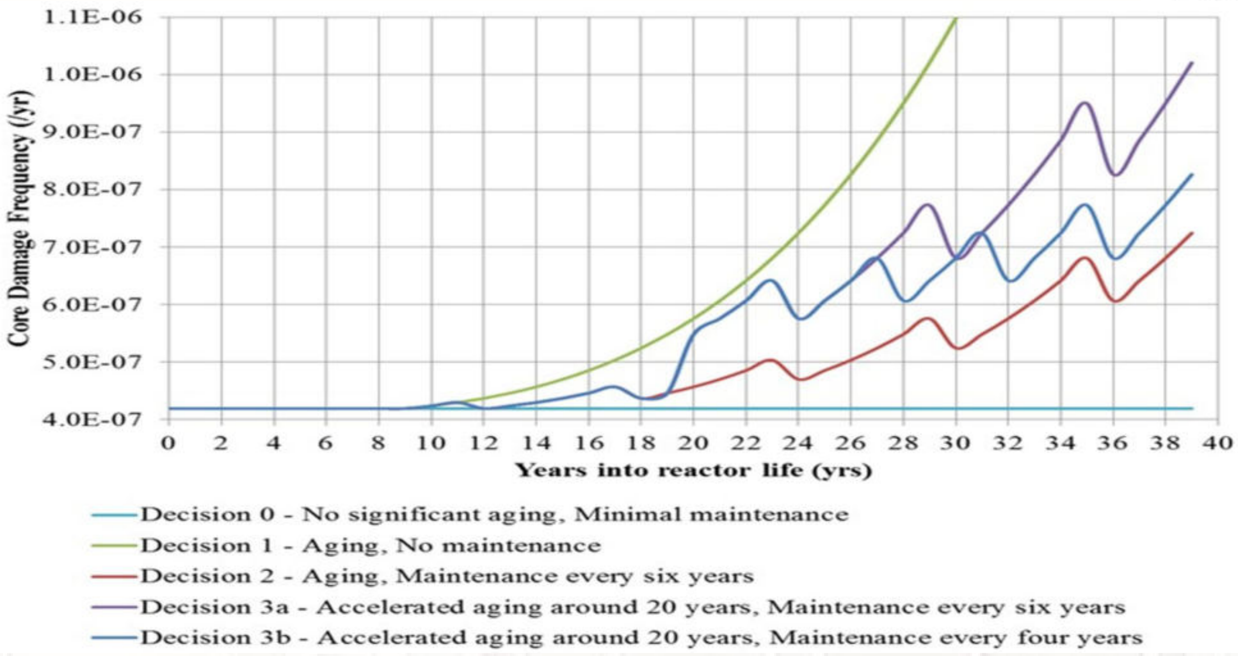
t_d - t_{mg}= Time available for repair / recovery /mitigation (referred as plant coping time)=C



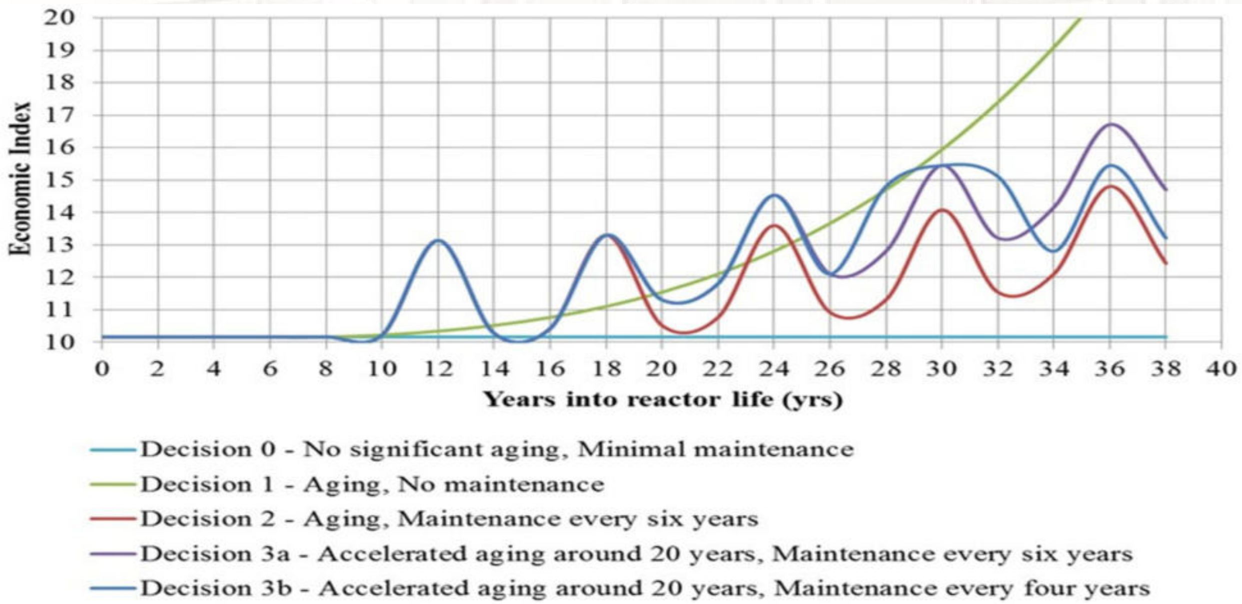
Research background & significance



CDF

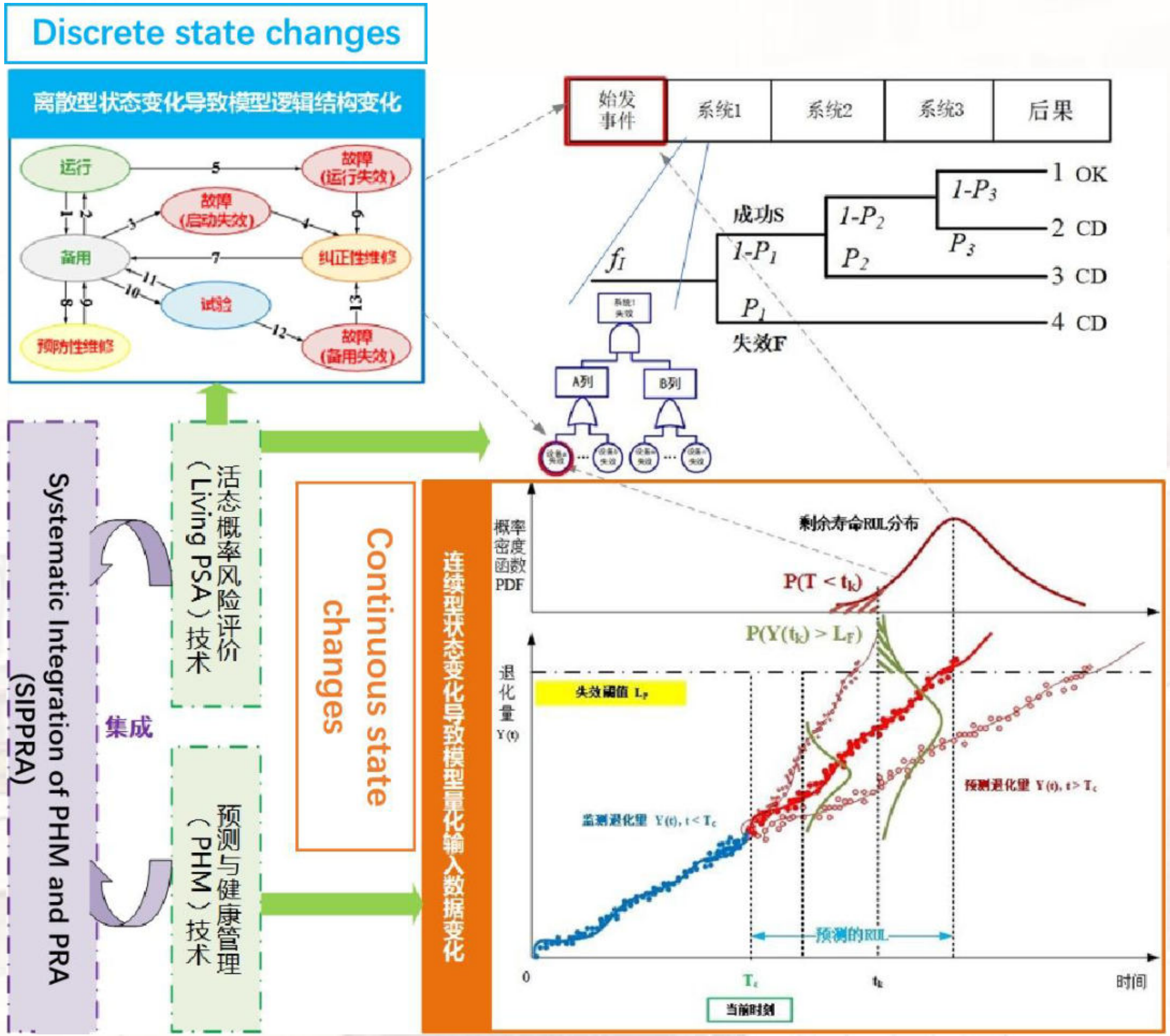


Economic Index

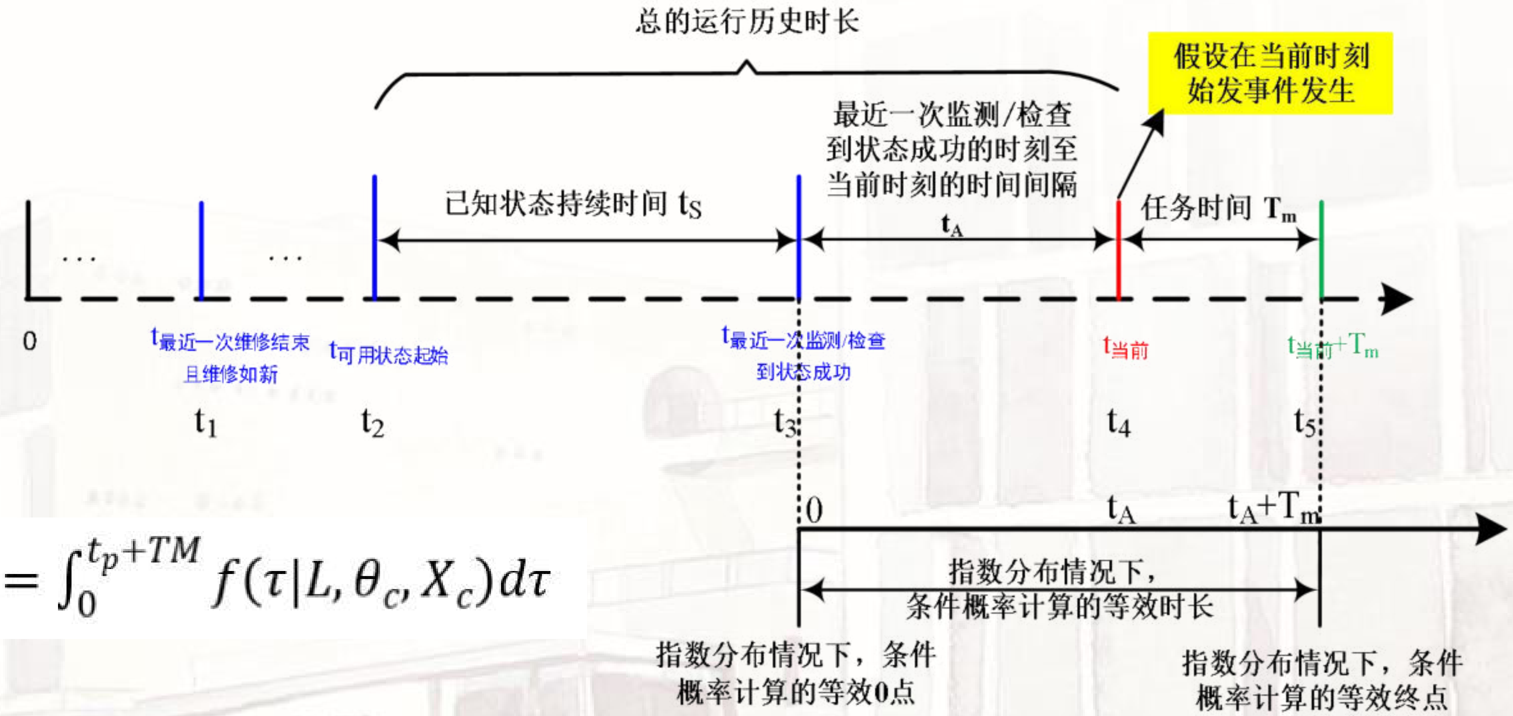


Technical roadmap

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY



Timeline design for risk monitoring/ prediction



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

Timeline design for risk monitoring/ prediction

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY

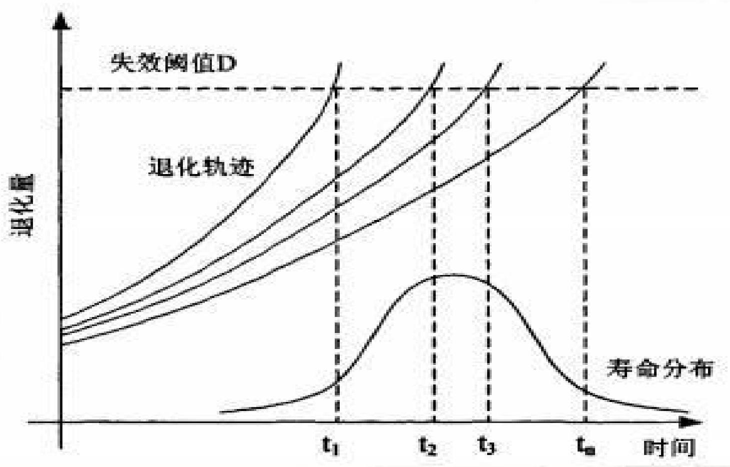
$$RUL = \inf\{t_R: X(t_c + t_R) \geq L\}$$

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

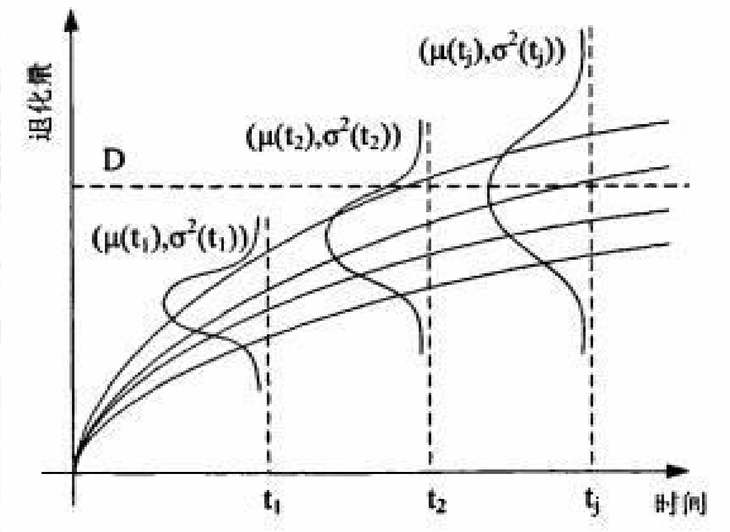
The concept of time-varying probability of failure (POF) based on performance degradation and its predictive theoretical methods

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

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

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY

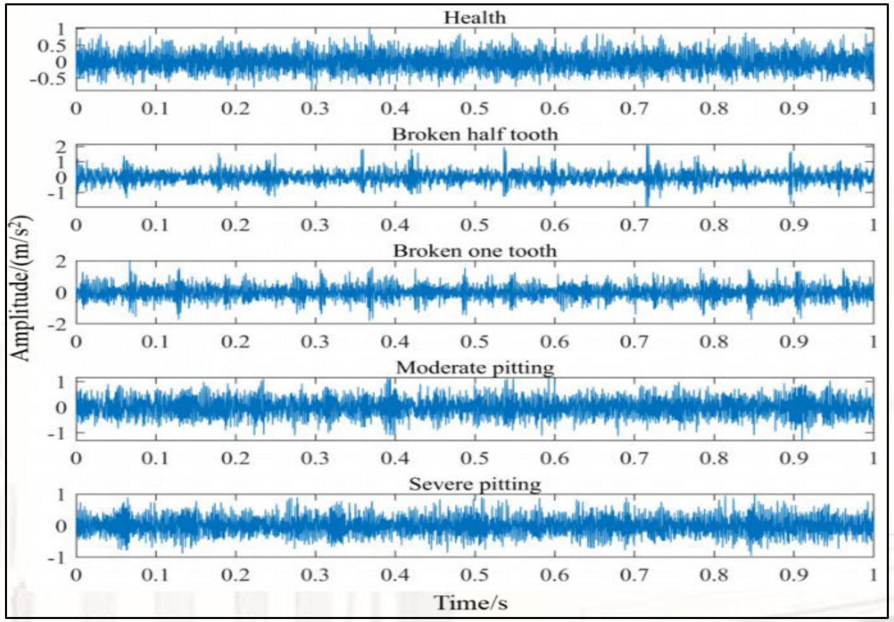
Fault experiments for over a year and lifescycle experiments for six months have been conducted on the circulating water pump, accumulating a large amount of data.

On-site data collection and data collection terminal

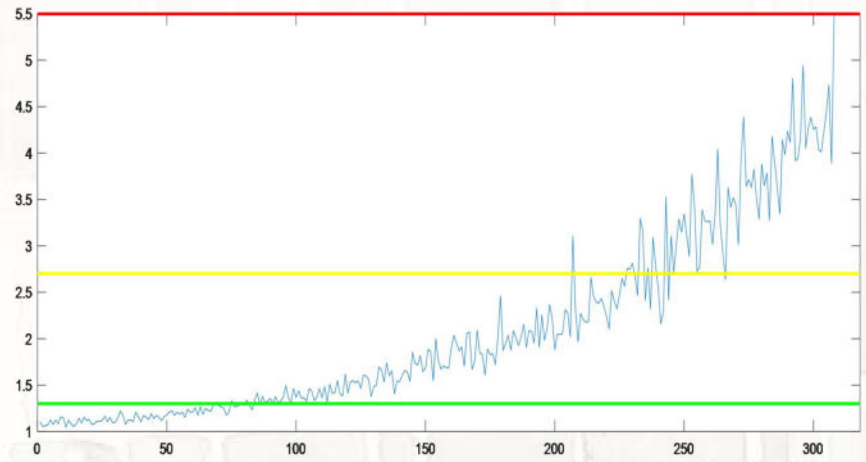
Accumulated multiple sets of fault data and full life data

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

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY



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 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.

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

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY

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.
- ϕ is the intercept term considered as a constant.
- θ and β are random parameters determining the slope of the model,
  - θ is lognormal-distributed
  - β is Gaussian-distributed.
  - At each time step t, the distribution of θ and β is updated to the posterior based on the latest observation of $h(t)$.
- ϵ 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

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY

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

名称 大小 类型 修改时间

第73天.json	第74天.json	第75天.json	第76天.json	第77天.json	第78天.json	第79天.json	第80天.json
第81天.json	第82天.json	第83天.json	第84天.json	第85天.json	第86天.json	第87天.json	第88天.json
第89天.json	第90天.json	第91天.json	第92天.json	第93天.json	第94天.json	第95天.json	第96天.json
第97天.json	第98天.json	第99天.json	第100天.json	第101天.json	第102天.json	第103天.json	第104天.json
第105天.json	第106天.json	第107天.json	第108天.json	第109天.json	第110天.json	第111天.json	第112天.json
第113天.json	第114天.json	第115天.json	第116天.json	第117天.json	第118天.json	第119天.json	第120天.json
第121天.json	第122天.json	第123天.json	第124天.json	第125天.json	第126天.json	第127天.json	第128天.json
第129天.json	第130天.json	第131天.json	第132天.json	第133天.json	第134天.json	第135天.json	第136天.json
第137天.json	第138天.json	第139天.json	第140天.json	第141天.json	第142天.json	第143天.json	第144天.json
第145天.json	第146天.json	第147天.json	第148天.json	第149天.json	第150天.json	第151天.json	第152天.json
第153天.json	第154天.json	第155天.json	第156天.json	第157天.json	第158天.json	第159天.json	第160天.json
第161天.json	第162天.json	第163天.json	第164天.json	第165天.json	第166天.json	第167天.json	第168天.json
第169天.json	第170天.json	第171天.json	第172天.json	第173天.json	第174天.json	第175天.json	第176天.json
第177天.json	第178天.json	第179天.json	第180天.json	第181天.json	第182天.json	第183天.json	第184天.json
第185天.json	第186天.json	第187天.json	第188天.json	第189天.json	第190天.json	第191天.json	第192天.json
第193天.json	第194天.json	第195天.json	第196天.json	第197天.json	第198天.json	第199天.json	第200天.json
第201天.json	第202天.json	第203天.json	第204天.json	第205天.json	第206天.json	第207天.json	第208天.json
第209天.json	第210天.json	第211天.json	第212天.json	第213天.json	第214天.json	第215天.json	第216天.json
第217天.json	第218天.json	第219天.json	第220天.json	第221天.json	第222天.json	第223天.json	第224天.json
第225天.json	第226天.json	第227天.json	第228天.json	第229天.json	第230天.json	第231天.json	第232天.json
第233天.json	第234天.json	第235天.json	第236天.json	第237天.json	第238天.json	第239天.json	第240天.json
第241天.json	第242天.json	第243天.json	第244天.json	第245天.json	第246天.json	第247天.json	第248天.json
第249天.json	第250天.json	第251天.json	第252天.json	第253天.json	第254天.json	第255天.json	第256天.json
第257天.json	第258天.json	第259天.json	第260天.json	第261天.json	第262天.json	第263天.json	第264天.json
第265天.json	第266天.json	第267天.json	第268天.json	第269天.json	第270天.json	第271天.json	第272天.json
第273天.json	第274天.json	第275天.json	第276天.json	第277天.json	第278天.json	第279天.json	第280天.json
第281天.json	第282天.json	第283天.json	第284天.json	第285天.json	第286天.json	第287天.json	第288天.json
第289天.json	第290天.json	第291天.json	第292天.json	第293天.json	第294天.json	第295天.json	第296天.json
第297天.json	第298天.json	第299天.json	第300天.json	第301天.json	第302天.json	第303天.json	第304天.json
第305天.json	第306天.json	第307天.json	第308天.json				

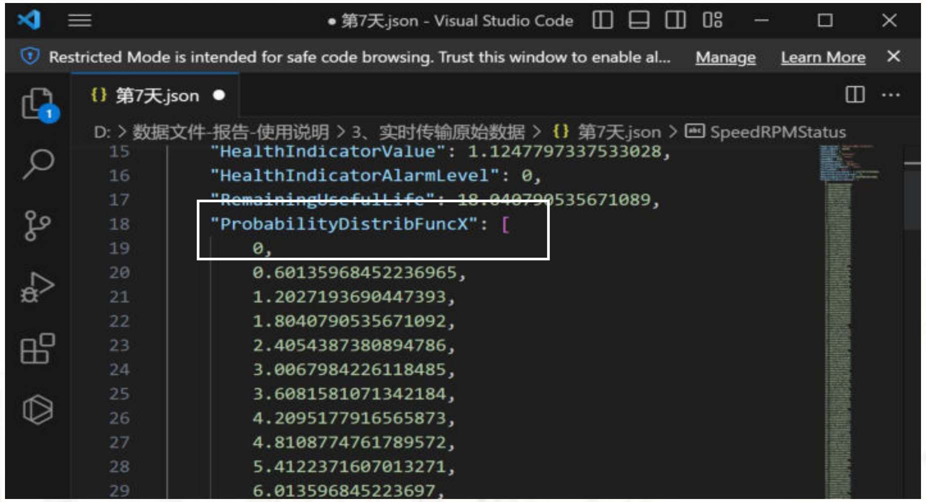
Data information of a specific day:

第194天.json - 记事本
文件(F) 编辑(E) 格式(O) 查看(V) 帮助(H)

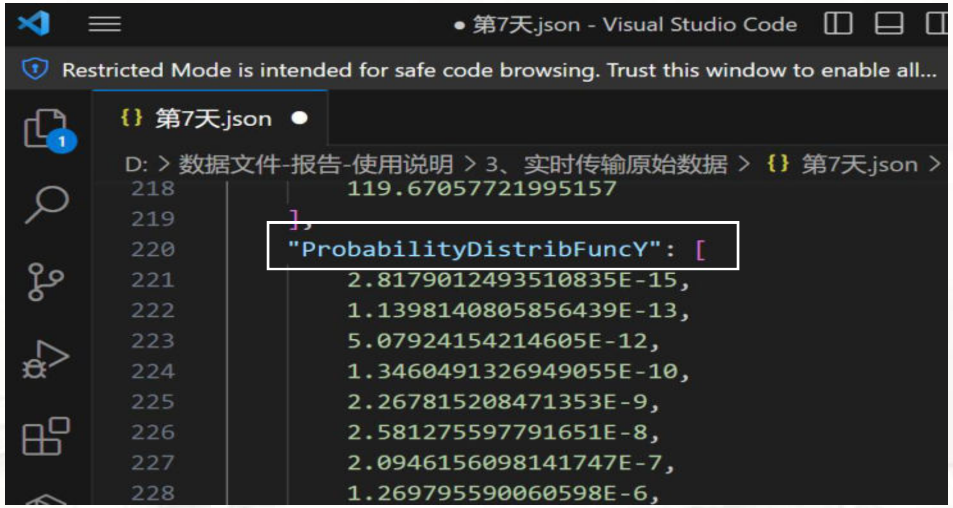
{"Status":"true","ErrorMessage":"NULL","BoxId":"AB30AA04","SamplingTime":"03-Jul-2023 13:06:44","SamplingRate":10240,"ChannelNum":1,"ChannelName":"齿轮箱振动","ChannelStatus":"正常","SpeedRPM":1920,"SpeedRPMStatus":"正常","TargetEquipment":"循环水泵","TargetOverallHealth":"健康","FailureMode":"劣化","HealthIndicatorValue":1.2810348032669805,"HealthIndicatorAlarmLevel":0,"RemainingUsefulLife":91.669576475797868,"ProbabilityDistribFuncX":
[0.21229004363706849,1.2173151692652091,2.2223402948933497,3.2273654205214908,4.2323905461496309,5.2374156717777725,6.2424407974059131,7.2474659230340537,8.2524910486621934,9.257516174290334,10.262541299918476,11.267566425546617,12.272591551174758,13.277616676802898,14.282641802431039,15.287666928059179,16.292692053687318,17.297717179315459,18.3027423049436,19.30776743057174,20.312792556199884,21.317817681828025,22.322842807456166,23.327867933084306,24.332893058712447,25.337918184340587,26.342943309968728,27.347968435596869,28.352993561225009,29.35801868685315,30.36304381248129,31.368068938109431,32.373094063737568,33.378119189365712,34.383144314993849,35.388169440621994,36.393194566250131,37.398219691878275,38.403244817506412,39.408269943134556,40.4132950687627,41.418320194390837,42.423345320018981,43.428370445647118,44.433395571275263,45.4384206969034,46.443445822531544,47.448470948159681,48.453496073787825,49.458521199415962,50.463546325044106,51.468571450672243,52.473596576300388,53.478621701928525,54.483646827556669,55.488671953184806,56.49369707881295,57.498722204441087,58.503747330069231,59.508772455697368,60.513797581325512,61.51882270695365,62.523847832581794,63.528872958209931,64.533898083838068,65.538923209466219,66.543948335094356,67.5489734607225,68.55399858635063,69.559023711978782,70.564048837606919,71.569073963235056,72.574099088863193,73.579124214491344,74.584149340119481,75.589174465747618,76.594199591375755,77.5992247170039,78.604249842632044,79.609274968260181,80.614300093888332,81.619325219516469,82.6243503451446,83.629375470772743,84.6344005964009,85.639425722029031,86.644450847657168,87.6494759732853,88.654501098913457,89.6595262245416,90.664551350169731,91.669576475797868,92.674601601426019,93.679626727054156,94.6846518526823,95.68967697831043,96.694702103938582,97.699727229566719,98.704752355194856,99.709777480822993,100.71480260645114,101.71982773207928,102.72485285770742,103.72987798333556,104.73490310896371,105.73992823459184,106.74495336021998,107.74997848584812,108.75500361147627,109.76002873710441,110.76505386273254,111.77007898836068,112.77510411398883,113.78012923961697,114.78515436524511,115.79017949087324,116.79520461650139,117.80022974212953,118.80525486775767,119.81027999338581,120.81530511901396,121.82033024464209,122.82535537027023,123.83038049589838,124.83540562152652,125.84043074715466,126.84545587278279,127.85048099841094,128.85550612403907,129.86053124966722,130.86555637529537,131.87058150092349,132.87560662655164,133.8806317521798,134.88565687780792,135.89068200343607,136.89570712906419,137.90073225469234,138.90575738032049,139.91078250594862,140.91580763157677,141.92083275720492,142.92585788283304,143.93088300846119,144.93590813408932,145.94093325971747,146.94595838534562,147.95098351097374,148.95600863660189,149.96103376223004,150.96605888785817,151.97108401348632,152.97610913911444,153.98113426474259,154.98615939037074,155.99118451599887,156.99620964162702,158.00123476725517,159.00625989288329,160.01128501851144,161.0163101441396,162.02133526976772,163.02636039539587,164.031385521024,165.03641064665214,166.04143577228029,167.04646089790842,168.05148602353657,169.05651114916472,170.06153627479284,171.066561400421,172.07158652604912,173.07661165167727,174.08163677730542,175.08666190293354,176.09168702856169,177.09671215418985,178.10173727981797,179.10676240544612,180.11178753107424,181.11681265670239,182.12183778233054,183.12686290795867,184.13188803358682,185.13691315921497,186.14193828484309,187.14696341047124,188.15198853609937,189.15701366172752,190.16203878735567,191.16706391298379,192.17208903861194,193.17711416424009,194.18213928986822,195.18716441549637,196.19218954112449,197.19721466675264,19

Calculate the POF based on the PDF for RUL

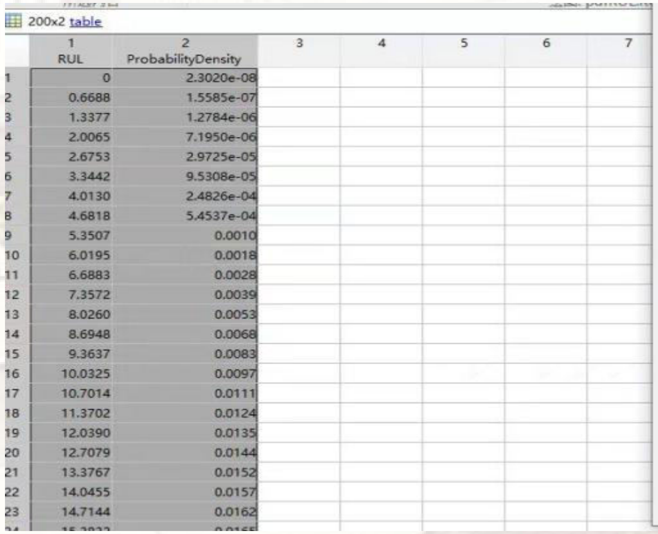
中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY



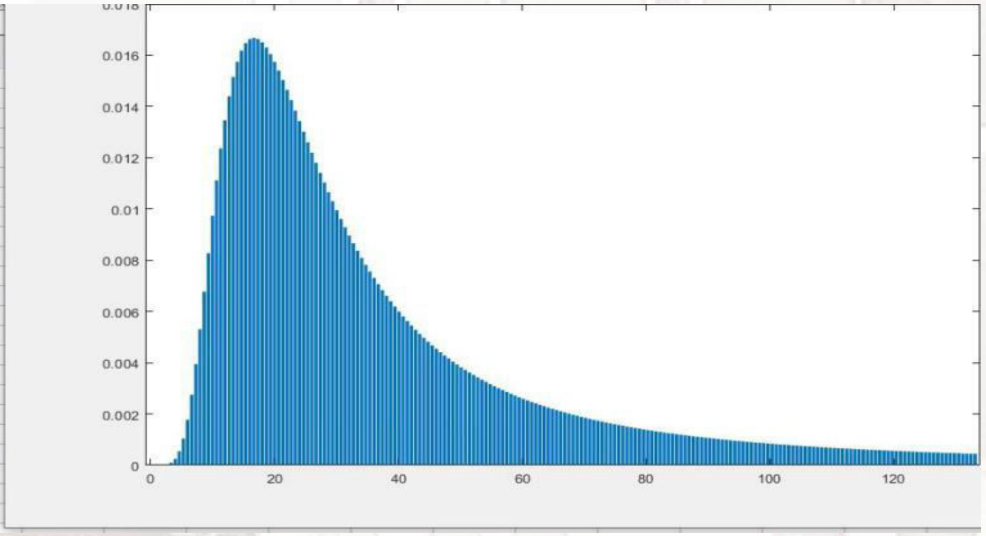
The X-axis of the PDF of RUL obtained from calculations



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

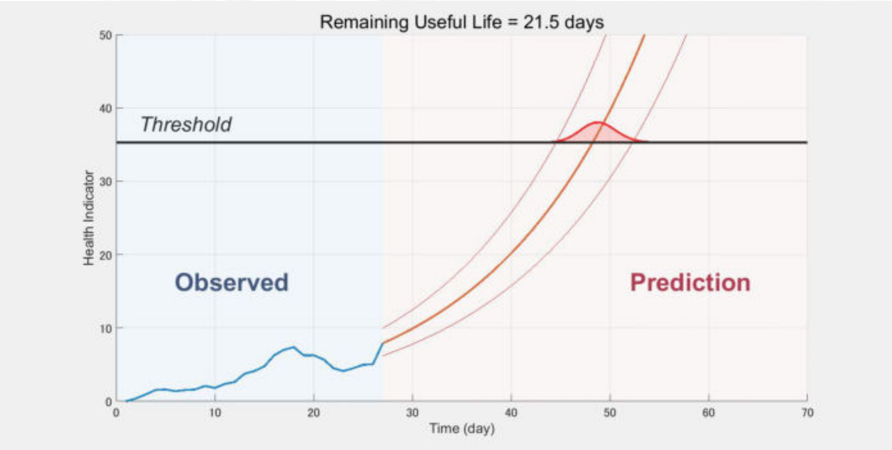

200x2 table

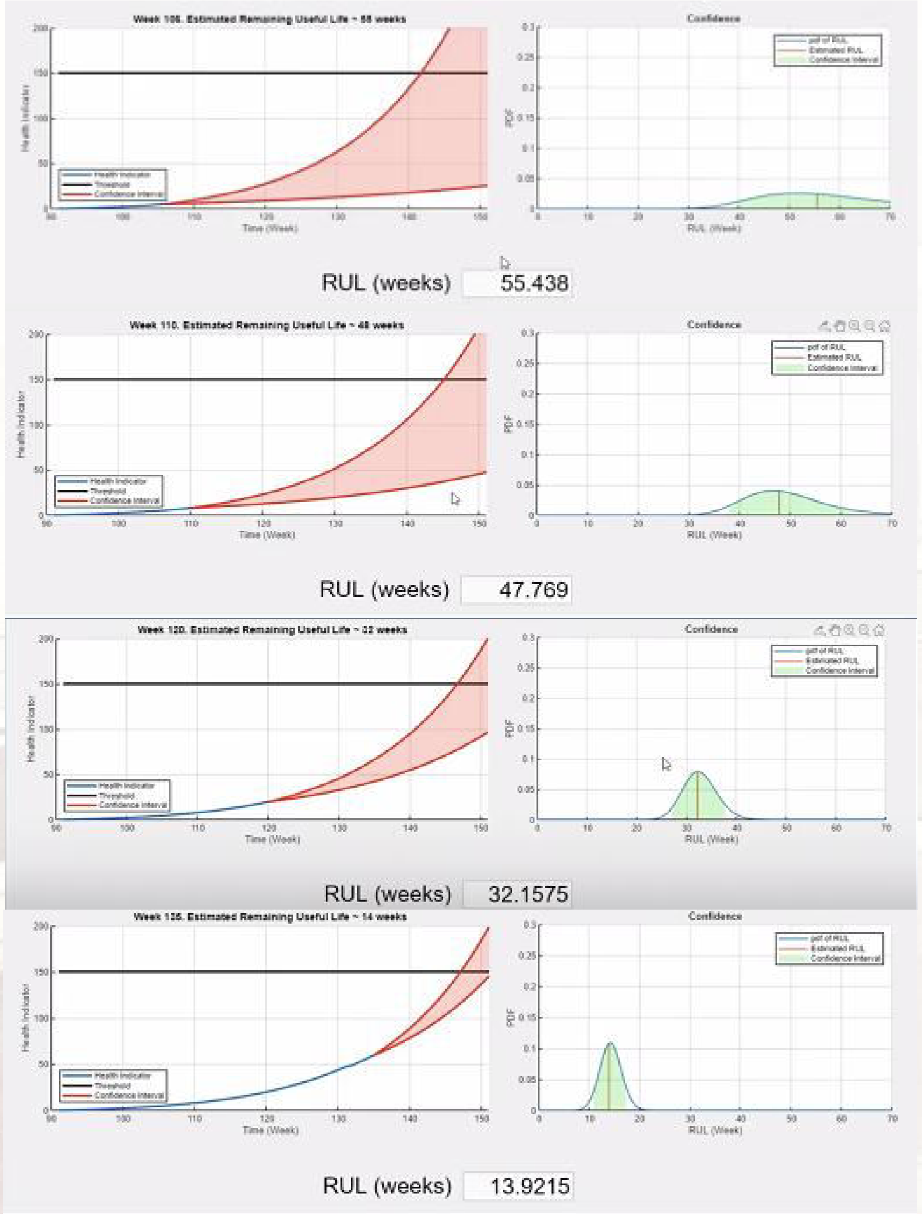
	RUL	ProbabilityDensity
1	0	2.3020e-08
2	0.6688	1.5585e-07
3	1.3377	1.2784e-06
4	2.0065	7.1950e-06
5	2.6753	2.9725e-05
6	3.3442	9.5308e-05
7	4.0130	2.4826e-04
8	4.6818	5.4537e-04
9	5.3507	0.0010
10	6.0195	0.0018
11	6.6883	0.0028
12	7.3572	0.0039
13	8.0260	0.0053
14	8.6948	0.0068
15	9.3637	0.0083
16	10.0325	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

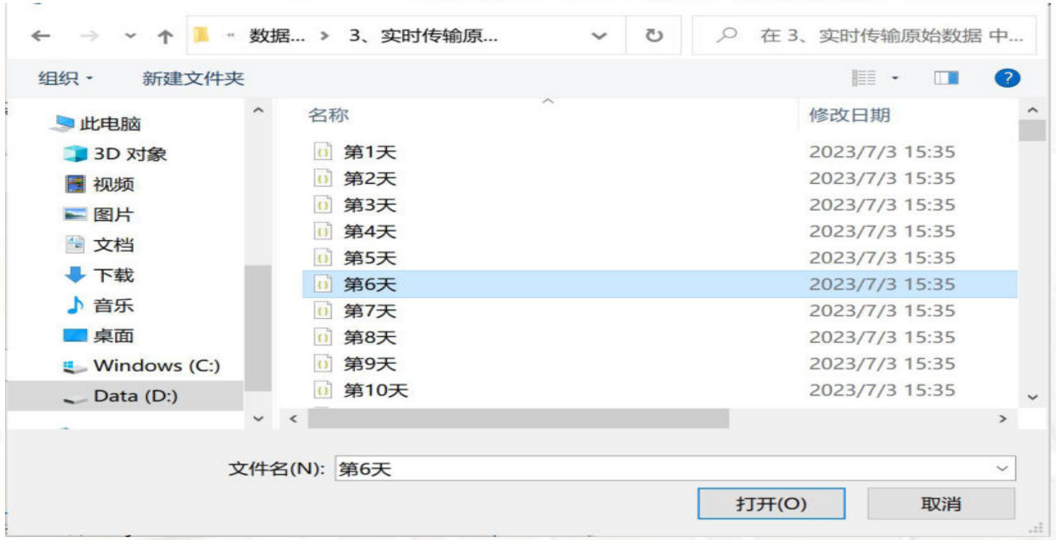
中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY



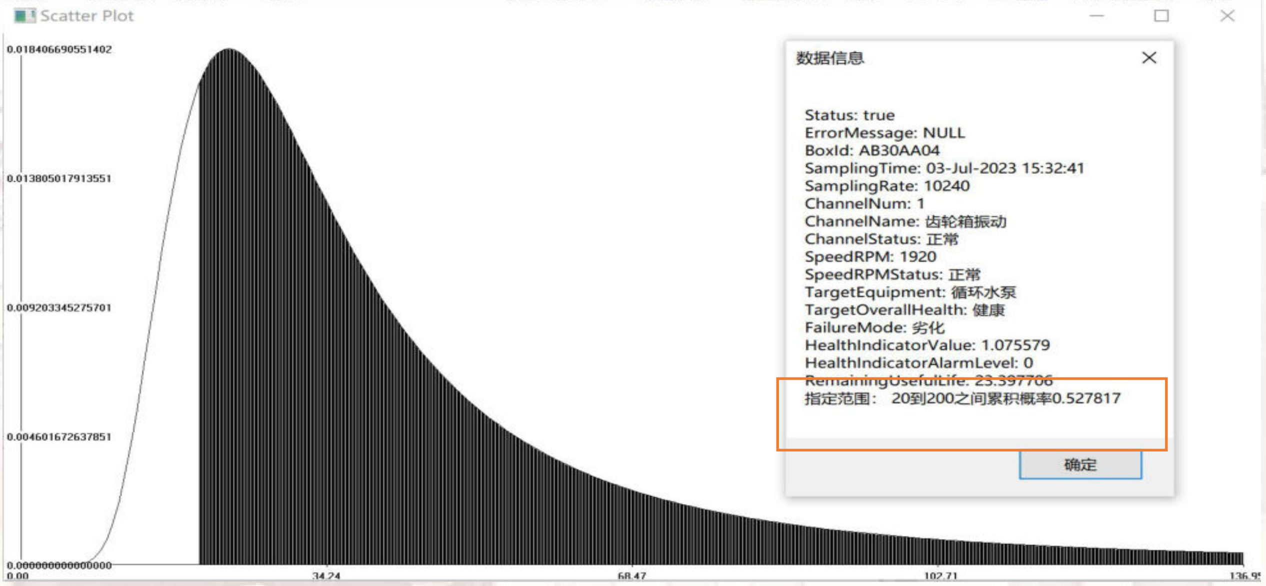


Calculate the POF based on the PDF for RUL

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY

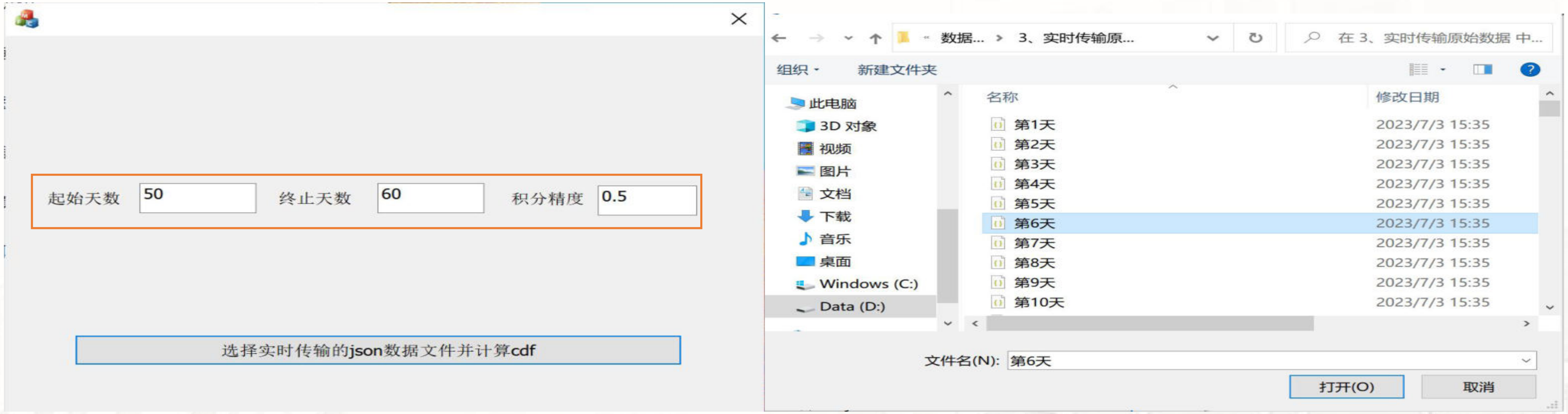


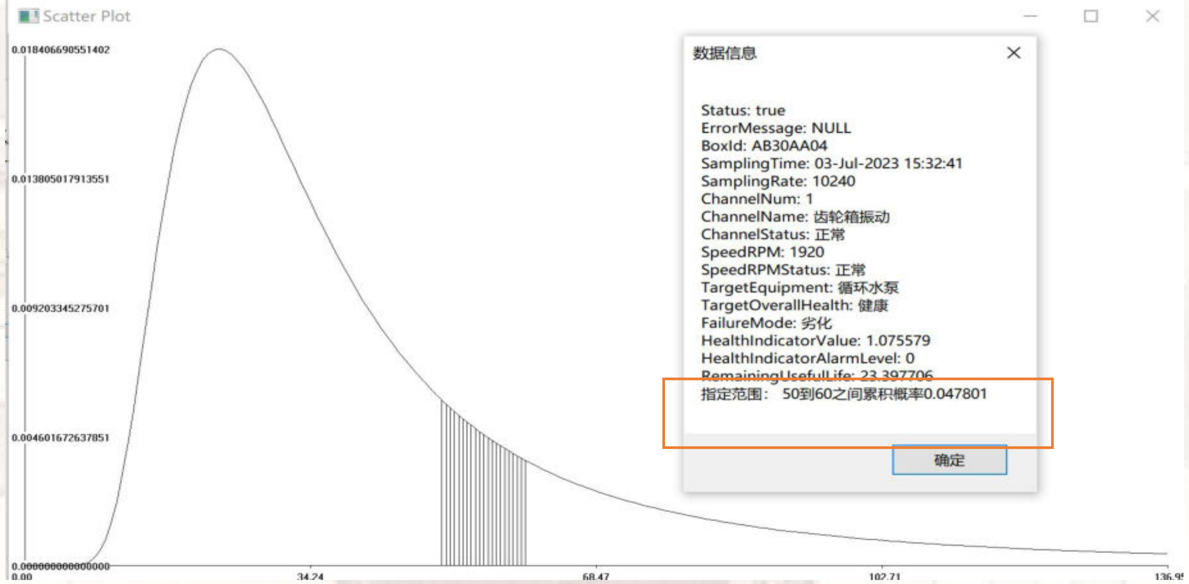
Calculate the failure probability within a specific time period by setting the time period and integration accuracy



Calculate the POF based on the PDF for RUL

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY

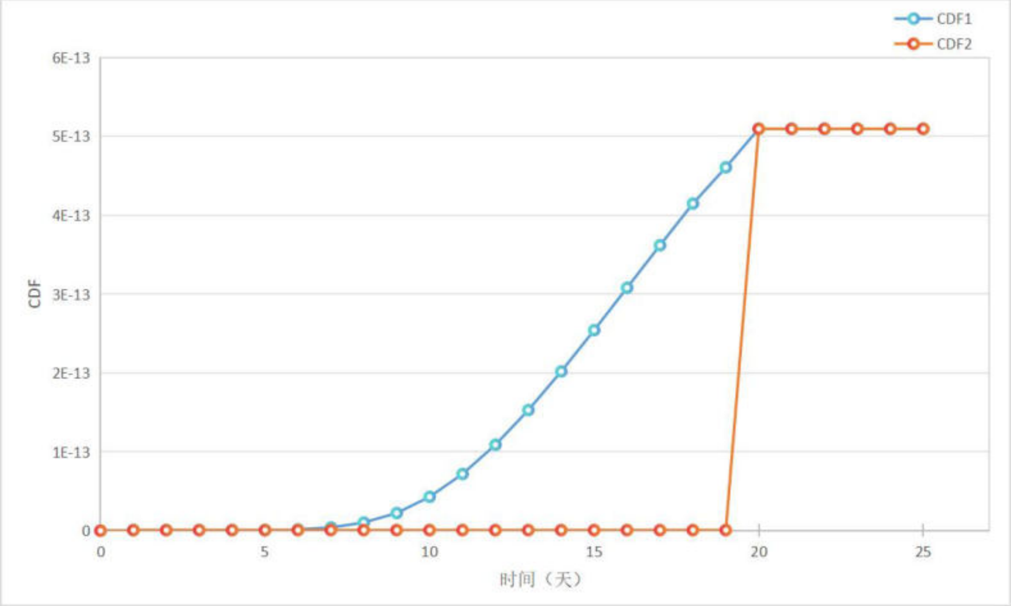




Case study on Core Damage Frequency (CDF)

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY

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

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY

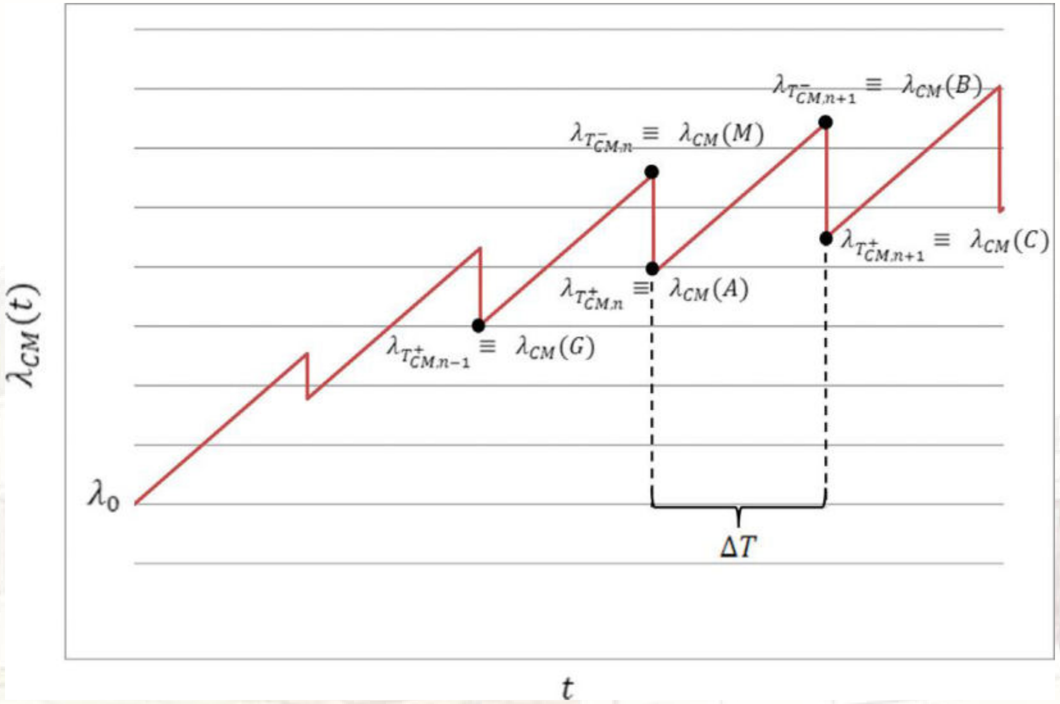


Illustration of $\lambda_{CM}(t)$

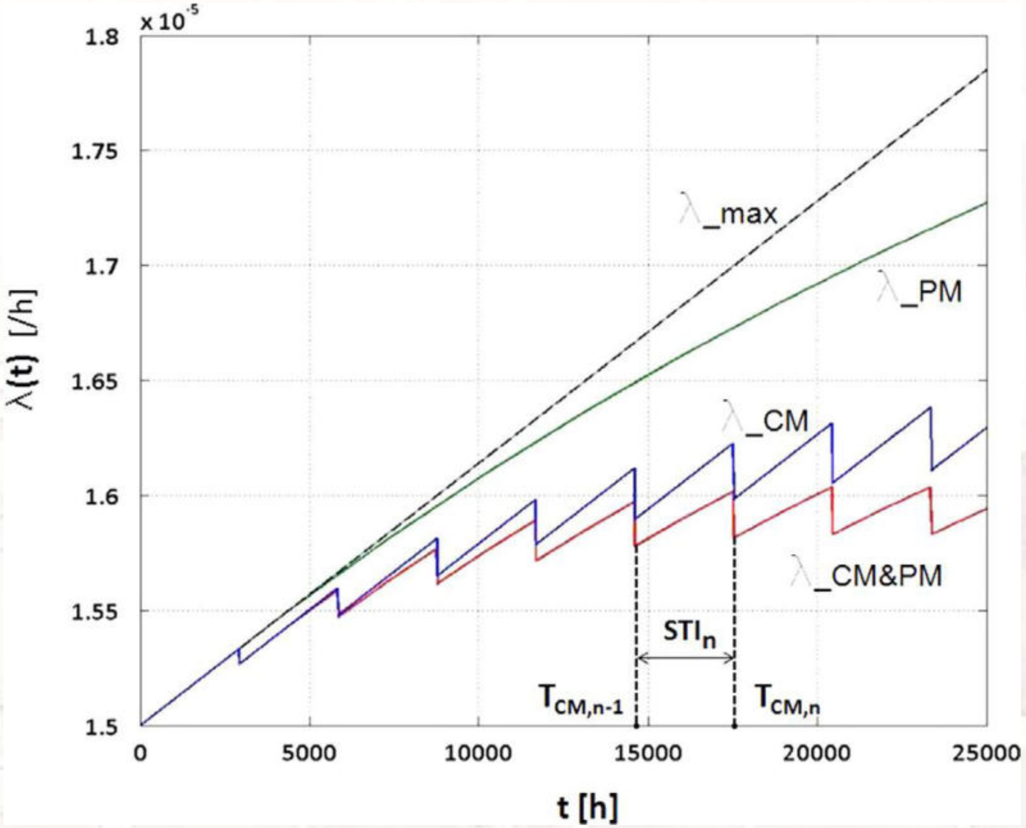
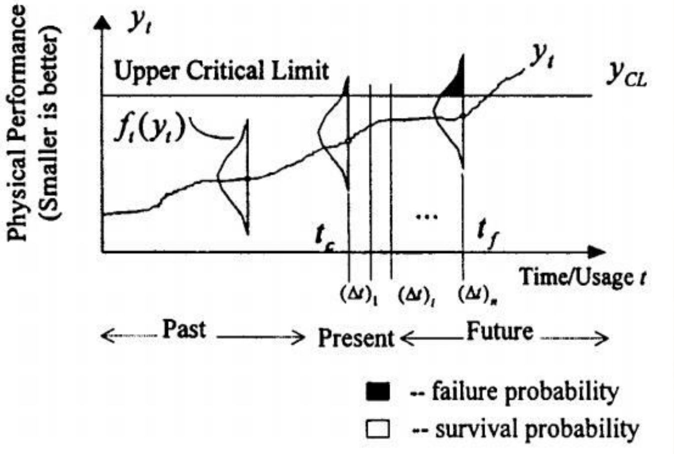


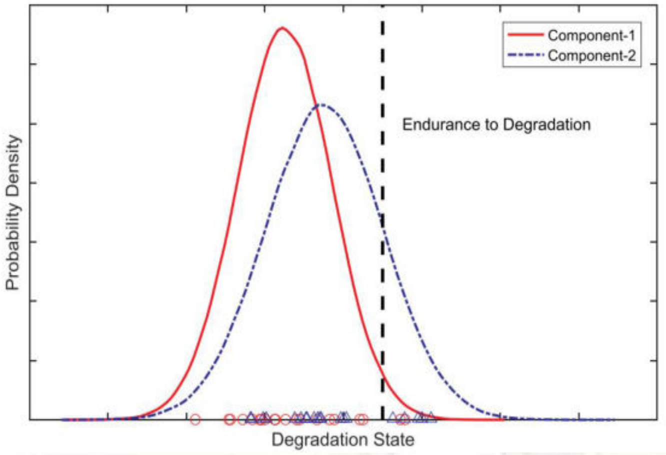
Illustration of the PM, CM and their combined effect on $\lambda(t)$

New CCF model for components under the degradation

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY

- 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.

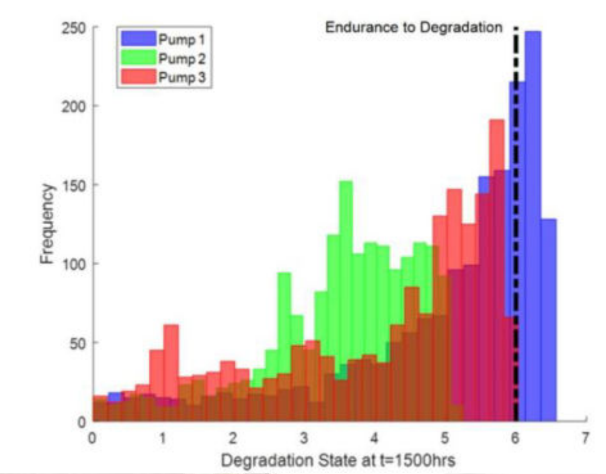


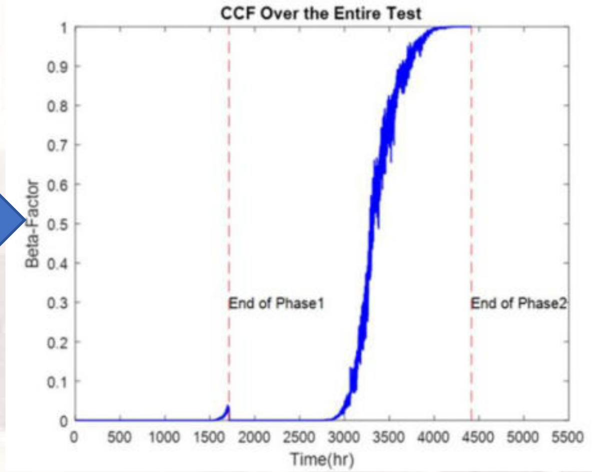


➢ At each time step, all samples from each component will be collected to describe the degradation state of each component.

➢ 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.



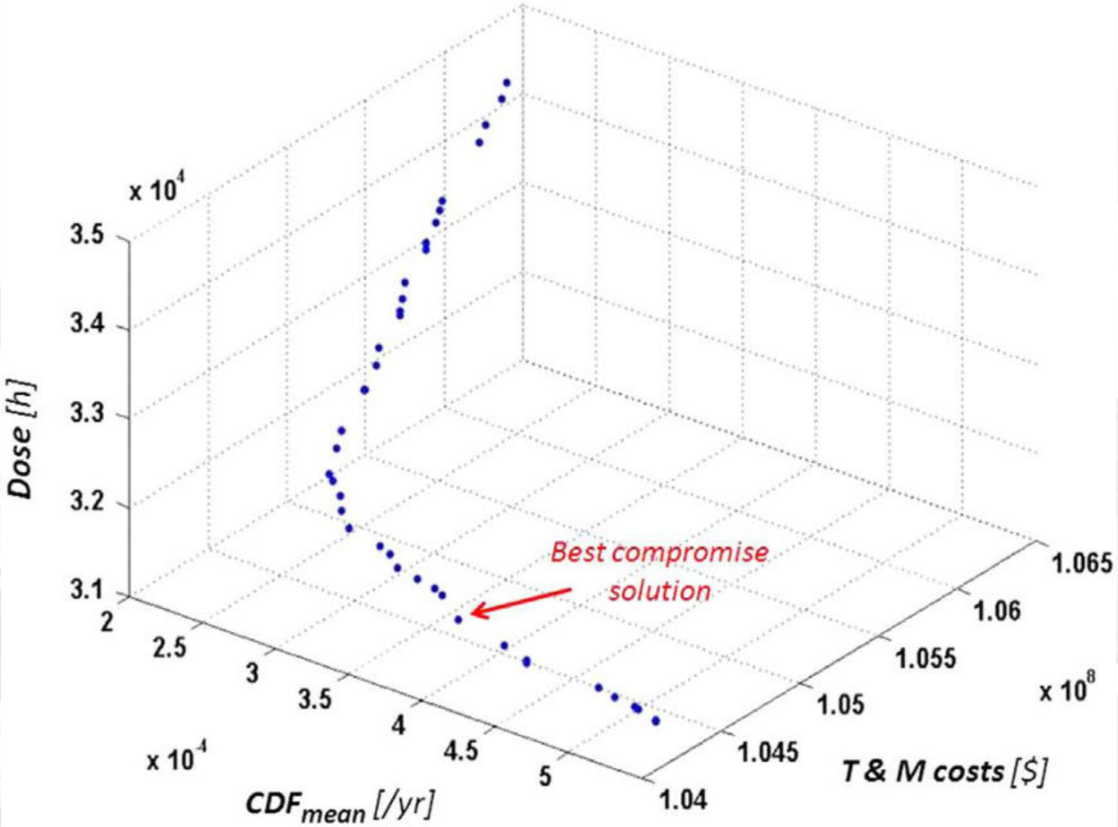


Plant-level multi-objective optimization

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY

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

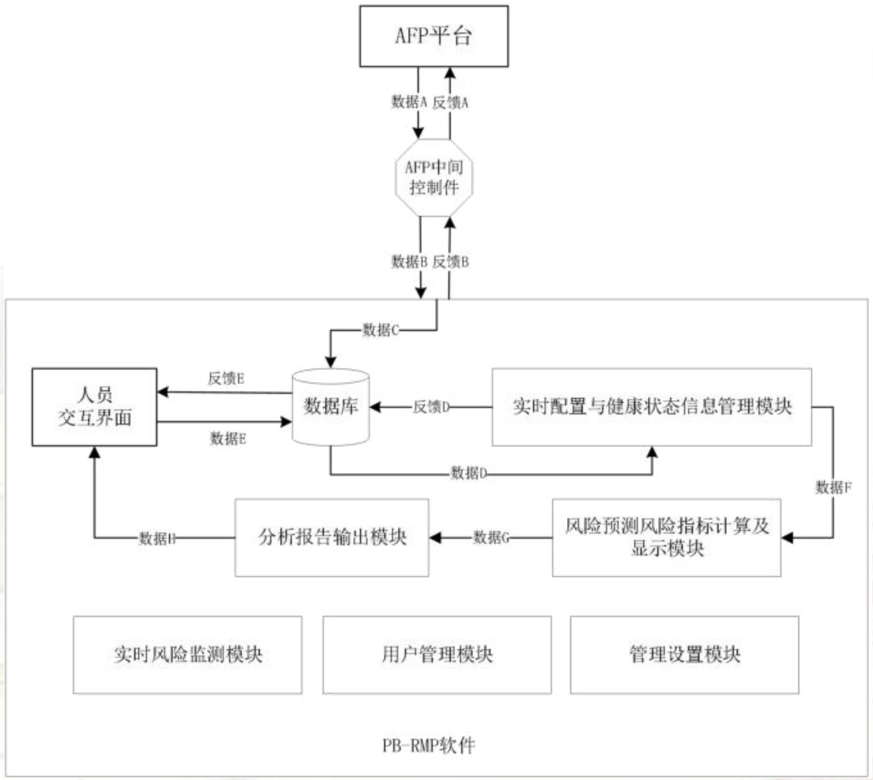


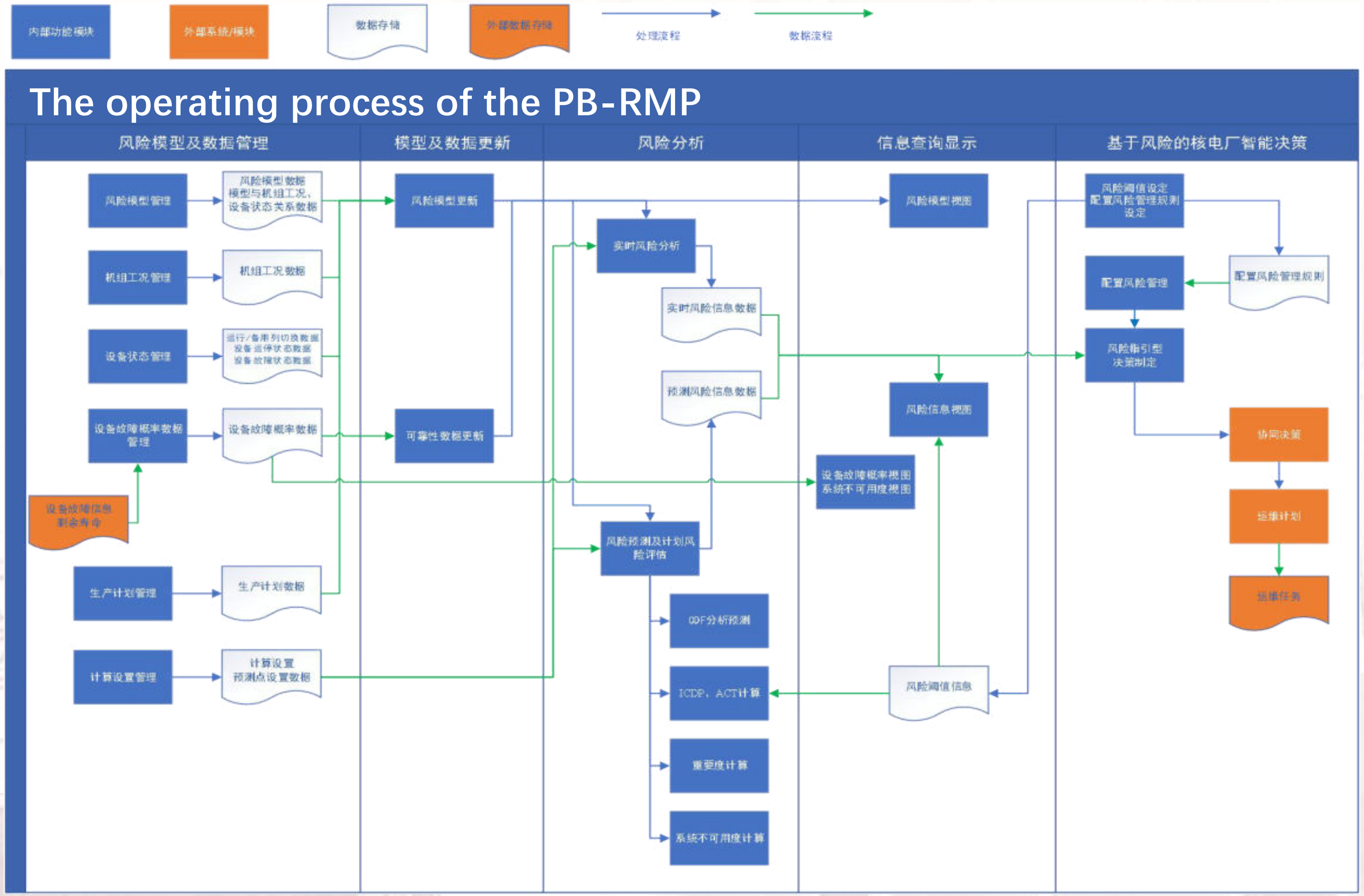
Pareto set of optimal solutions

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

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY

The data architecture of the PB-RMP

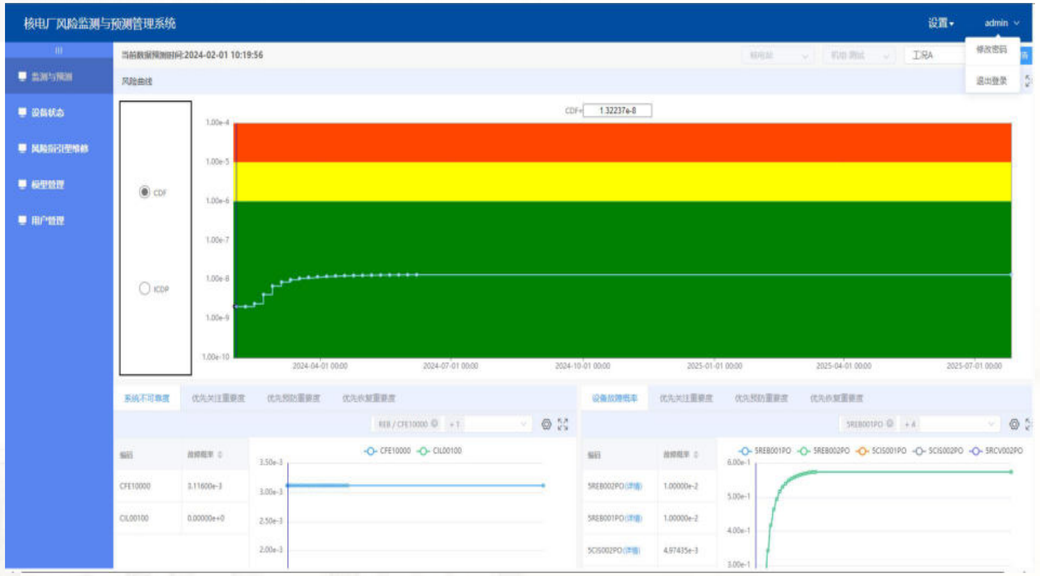


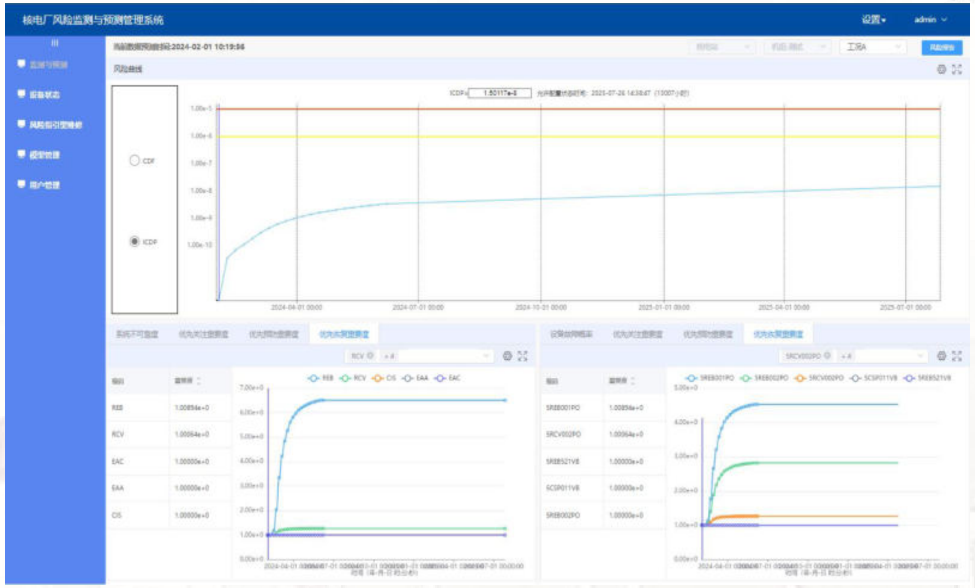


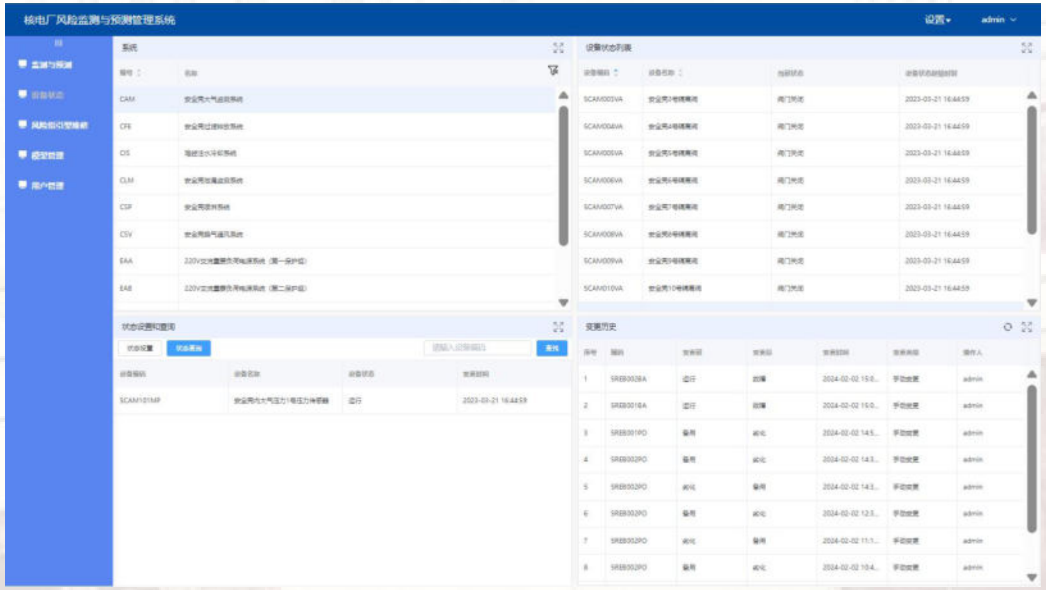
The operating process of the PB-RMP

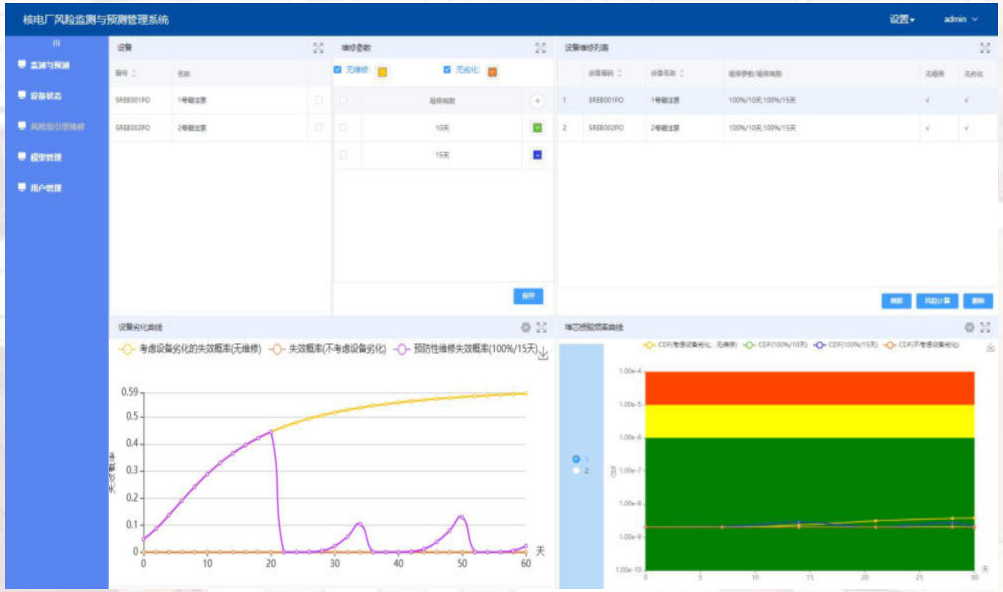
The user interfaces of the PB-RMP

中国核能与安全高等研究院
INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY









Thanks for your attention!

中国核能与安全高等研究院

INSTITUTE FOR ADVANCED STUDY IN NUCLEAR ENERGY & SAFETY