Risk Monitoring for Nuclear Power Plant Applications using PRA

Nuclear Engineering, Ltd. (Osaka, Japan)
KURAMOTO Takahiro

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Company Profile

- **KANSAI (The Kansai Electric Power Co., Inc.)**
  - Located in the center of JAPAN and supply electrical power in the “KANSAI” area.
  - Possesses 11 PWRs and is the second largest producer of electrical power in Japan.


- **NEL (Nuclear Engineering, Ltd.)**
  - Funded by KANSAI in order to supply and upgrade engineering services which enhance the safety and reliability of nuclear power plants.
  - Perform PRA (especially Level 1, internal events, external events).
  - Use PRA for the Risk informed Activities, and so on.

  [http://www.neltd.co.jp/index_eng.html](http://www.neltd.co.jp/index_eng.html)
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Introduction

- The results obtained by probabilistic risk assessment (PRA) provide useful risk information that can be utilized in identifying plant vulnerabilities, establishing plant maintenance programs, and revising rules and guidelines. To facilitate the use of PRA, the government and nuclear industry is actively working on the preparation of regulatory guidelines and industry standards and considering the application of risk-informed approaches to actual plants.

- It is necessary to continually monitor the risks depending on changing plant conditions, such as core damage, in future risk-informed applications. For this purpose, risk monitoring system should be developed.

- COSMOS is a risk monitoring system developed by Nuclear Engineering Ltd. (NEL) for Level 1 PRA for at-power and shutdown operation modes, which will be applied to plant operation and maintenance on a risk-informed basis. COSMOS can provide complete linkage with the integrated PRA tool RISKMAN, which has been widely adopted by plants at home and abroad.
1. Current Status of PRA, Risk informed Activities and Risk Monitoring in Japan
Probabilistic Risk Assessment (PRA)

Systematic and Comprehensive Methodology to Evaluate Risks associated with a Complex Engineered Technological Entity (such as a Nuclear Power Plant (NPP))
PRA Answers 4 Fundamental Questions

1. What can go wrong?
   i.e., what are the scenarios?

2. How likely is it?
   i.e., what are the scenario frequencies?

3. What are the consequences?

4. How do uncertainties impact the above answers?
## Assessment Type of PRA for NPP

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Level 1</strong></td>
<td>estimates the frequency of accidents that cause damage to the nuclear reactor core. This is commonly called core damage frequency (CDF).</td>
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<tr>
<td><strong>Level 2</strong></td>
<td>which starts with the Level 1 core damage accidents, estimates the frequency of accidents that release radioactivity from the nuclear power plant.</td>
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<tr>
<td><strong>Level 3</strong></td>
<td>which starts with the Level 2 radioactivity release accidents, estimates the consequences in terms of injury to the public and damage to the environment.</td>
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### Event Types

- **Plant Operation (At-power)**, **Low-Power & Shutdown**
- **Internal Events**: events originating within a NPP, e.g., Loss of Coolant Accident (LOCA), Transient
- **External Events**: events originating outside a NPP, e.g., Seismic, Floods (Tsunami)
Utilization of PRA

- Risk Level and Risk Profile Confirmation
- High Risk Equipments and Systems Identification
- Risk informed Decision Making of Maintenance Prioritization
- Graded-QA, On-Line Maintenance w/ Tech-Spec Changing & Risk Monitoring, RI-ISI, RI-IST, etc
Status of PRA in Japan

- All in-service commercial NPPs (BWR/PWR) have been already evaluated Internal events CDF (Level 1) and CFF (Level 2).
- Utilities should evaluate the risk (i.e., CDF/CFF at operational mode and CDF at shutdown mode) of their own plants in the Periodical Safety Review (PSR) at least once per 10 years.
- The external events PRA has been much studying recently (especially Seismic and Tsunami PRA).
- Also, towards to the Risk informed Activities using PRA result, utilities pay much efforts to update the PRA model and documentations to meet the requirements of standards and peer review.
Status of Risk informed Activities in Japan

- Preparing Regulatory Guideline (GL) for Risk informed Regulations

- Japanese Regulatory, NISA has Published Trial-GL at 2005
Status of Risk informed Activities in Japan (cont.)

- Many Technical Standards regarding PRA and Risk informed Activities Published and Preparing under Atomic Energy Society of Japan (AESJ)
  - Internal Operational PRA
  - Internal Shutdown PRA
  - Internal Flooding PRA
  - Internal Fire PRA
  - Seismic PRA
  - Tsunami PRA
  - PRA Parameter
  - Risk informed Activities

- Comprehensive PRA Peer Review Planning
- Effective Risk informed Activities Enforcing and Planning
  - Outage Schedule Optimization w/Risk Monitoring
  - On-Line Maintenance (OLM) w/ Risk Monitoring
  - RI-ISI, etc.
2. The Achievements of Risk informed Activities in U.S.
History of Risk informed Regulations in U.S.

- 1986.8 NRC: Policy Statement of “Safety Goal”
- 1996.8 ASME: Code Case of “RI-ISI, RI-IST”
- 1998.8 NRC: Regulatory Guides for Risk informed Regulations)

<table>
<thead>
<tr>
<th>Guide Number</th>
<th>Description</th>
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<tbody>
<tr>
<td>R.G.1.174</td>
<td>General</td>
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<tr>
<td>R.G.1.175</td>
<td>RI-IST</td>
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<tr>
<td>R.G.1.176</td>
<td>Graded QA</td>
</tr>
<tr>
<td>R.G.1.177</td>
<td>T-Spec (AOT/STI Change)</td>
</tr>
<tr>
<td>R.G.1.178</td>
<td>RI-ISI</td>
</tr>
</tbody>
</table>

- 2000.2 Industry: Maintenance Rule (NUMARC93-01, Rev1)
Reduction of Power Generation and Maintenance Cost in U.S.

- Easing of Restrictions
- Power Uprate
- Long-term Cycle Operation
- Shortening of Outage Period
- Outage Schedule Optimization (Shutdown Risk Evaluation)
- AOT Extension
- At-Power Risk Monitoring
- Support
- Reduction of Power Generation Cost
- Rise of Availability
- Reduction of Maintenance Cost
- On-Line Maintenance (OLM)
- RI-ISI, RI-IST

Support
On-Line Maintenance (OLM)

- In the past, most planned maintenance works in NPPs were performed during an outage.
- Currently, US utilities have been performing planned maintenance on safety related components while the plant is at-power.
- By shifting certain planned maintenance activities normally performed during an outage (in particular, a refueling outage) to during power operation, the outage duration can be significantly reduced.
- US availability and capacity factor measures have significantly improved (a portion of this improvement can be credited to OLM).
On-Line Maintenance (OLM) (Cont.)

- Plant configurations are not limited by plant Technical Specifications in all cases.
- US NRC has expressed concern that utilities may not be adequately considering the risks of extended operation in degraded plant configurations.
- Utilities have responded to this concern using Risk Monitoring.
- Risk monitoring during OLM is now required under Paragraph a(4) of 10 CFR 50.56 (Maintenance Rule).
Application Example for On-Line Maintenance (OLM) - Salem NPP (1/3)-

- Use Risk Matrix with the Out-Of-Service (OOS) combinations of the risk-related components in OLM planning stage.
- Risk Matrix Describes the risk level for the 2 components’ OOS combinations. Plant Staffs should Evaluate the risk even in the night time on demand.
- The risk level (Instantaneous CDF) of the OOS combinations is classified by 3 colors:
  - **Red:** $1 \times 10^{-4}$/year CDF$_{ins}$
    - Cannot Allow OLM.
  - **Yellow:** $5 \times 10^{-5}$/year CDF$_{ins}$ $1 \times 10^{-4}$/year
    - Can Allow OLM with applicable compensative Measures.
  - **Green:** CDF$_{ins}$ $5 \times 10^{-5}$/year
    - Can Allowable OLM with no Problem.

- During OLM enforcement, Risk Monitoring with the actual plant configuration should be done. (Requirements from Maintenance Rule/ NUMARC93-01)
Application Example for On-Line Maintenance (OLM) - Salem NPP (2/3)-

An Example of Risk Matrix
An Example of 12 weeks OLM Schedule
3. Risk Monitoring
Risk Monitoring

- Risk Monitoring is the essential item for the risk informed activities.
- In many countries, Risk monitoring has been installed for their own risk-informed applications consistent with the PRA models.
- 2 key issues:
  - “shutdown risk evaluation for every outage”
  - “At-power risk monitoring in case of On-Line Maintenance”
Risk Monitoring (Risk Monitor) Definition by IAEA

- **Risk Monitor** is a plant specific real-time analysis tool used to determine the instantaneous risk based on the actual status of systems and components.
- At any given time, the Risk Monitor reflects the current plant configuration in terms of the known status of the various systems and/or components.
- The Risk Monitor is based on, and is consistent with, the Living PRA. It is updated with the same frequency as the Living PRA.
- The Risk Monitor is used by plant staff in support of operational decisions.
Risk Monitoring Benefits

- Manage plant operational safety
- Support scheduling activities
- Achieve greater flexibility in plant operations
- Provide justifications for carrying out On-Line Maintenance (OLM)
- Provide information on the risk importance of components that are in service as well as out of service
(Regular) PRA v.s. Risk Monitoring

- Regular PRA provides average risk, $CDF_{avg}$, using average initiating event frequencies and maintenance unavailabilities.
- Risk monitoring provide point-in-time risk, $CDF(t)$, for the current plant configuration and environmental factors.
How should be Risk Monitoring Used?

On-Line for actual control and maintenance:
- Risk informed Information for Decision Making
- Monitoring the Risk qualitatively and quantitatively
- Calculating Allowed Outage Time (AOT) and Cumulative Risk

Off-line for planning:
- Future Maintenance Outages
- Long term Risk profiling
- Analysis of Cumulative Risk
- Evaluation in case of unplanned events occur
- Feedback – lessons learnt
How should be Risk Monitoring Used? (cont.)

Provides…

– Information about which components should be returned to service prior to taking others Out-Of-Service and which components are the most important ones during maintenance outages

– Input into whether more maintenance can be carried out on-line without increasing the overall risk

– Input into maintenance planning to avoid peaks in risk
Major Risk Monitoring Tools Used in U.S.

• EOOS Configuration Risk Monitor
  - Developed by EPRI

• Safety Monitor™
  - Developed by Scientech

• PARAGON™ (ORAM-SENTINEL)
  - Developed by ERIN

• Or, Some In-house Tools by each Utility
Risk Monitoring Example – San Onofre NPP; Safety Monitor™ –
4. Risk Monitoring System
COSMOS Development
Outline of COSMOS

< PRA Software in KANSAI/NEL >

NELFT

Fault Tree Drawings w/ FT checking Enhancements

RISKMAN

RISKMAN Database

INPUT generating

ATORAS

OUTPUT extracting

COSMOS-SD

Outage Risk Evaluations

Risk Monitoring

COSMOS-FP

RM2R

RISEDIT

Documentations

PRA Model Descriptions

PRA Results

n el
General Features of COSMOS

- COSMOS is a level-1 and internal event risk monitoring tool up to now.
- COSMOS has completely linkage to RISKMAN and the model.
  - COSMOS does not require special PRA models for RISKMAN and CDF sequences which previously stored.
- COSMOS has 2 separated modules “COSMOS-FP” and “COSMOS-SD” for each PRA quantification. COSMOS change the quantification logic between “COSMOS-FP” and “COSMOS-SD” with each usage.
Key Features for Evaluation of COSMOS

- “COSMOS-FP” follows these steps:
  1. Set the failure probability of basic event related to the outage equipment to 1.0
  2. Quantify the Fault Tree (FT)s by the BDD method
  3. Quantify the Event Tree (ET)s. Only the top events affected by the outage are recalculated.
   “COSMOS-FP” keeps the quantification results inside own database with one unique outage equipment case for the reduction of calculation time.

- COSMOS-SD” is mainly used for the risk evaluation of refuelling shutdown repeatedly and cyclically, so the quantification logic is different from “COSMOS-FP”.
  In “COSMOS-SD” quantification, FT re-quantification is not done. “COSMOS-SD” sets the ET branching ratios (the split fractions) corresponding to various alignments in the ETs, and re-quantifies the ETs directly.
Key Features for Evaluation of COSMOS (cont.)

Conventional Risk Monitor

- Quantify Core damage frequency based on the core damage sequences or cutsets previously stored.
  - The calculation precision is strongly dependent on the number of the prepared sequences.
- Have to identify the outage equipments, before picking up core damage sequences.

COSMOS

- Quantify Core damage frequency directly from FTs and ETs quantification.
  - COSMOS does not require the core damage sequences or cutsets previously stored.
- Treat all basic events for the input conditions. (COSMOS-FP)
COSMOS-FP (for at-power)

COSMOS-GUI
- Equipment Status (User Inputs)
- Schedule Making / COSMOS-FP (COSMOS AUTO.EXECUTE)
- User Interface for Maintenance Schedule Inputting and calculated CDF Outputting for each condition / COSMOS-FP (COSMOS AUTO.EXECUTE)

COSMOS-DB
- Status of Equipments and Quantification results Setting

COSMOS QUANTIFICATION ENGINES and SYSTEMS
- FT Re-quantification ARALIA (BDD Method)
- ET Re-quantification ET ENGINE

RISKMAN (OPENINSIGHT)
- PRA MODEL
(Using XML Format)

Communications Control

Maintenance Schedule File
Key Features of COSMOS-FP

- Assume to use COSMOS-FP for scheduling of at-power On-Line Maintenance.

- Restore sets of status of equipments and the quantification results to the database. COSMOS-FP utilizes the database for speeding calculation.

- Have a feature of successive execution of FTs and ETs corresponding to the On-Line Maintenance equipments.
On-Line Maintenance Scheduling and Risk Evaluation (COSMOS-FP)

- **Input Generation**
  - Gantt Chart Operation
  - Inputs referred to Calendar
  - Inputs from Formatted file (XML)
  - “In-service” or “Standby” or “Out-of-Service” Switching

- **Result Indication**
  - Time dependent CDF and/or ICCDP/Cumulative ICCDP Outputs
  - The CDF sequence outputs by each time phase
  - The core damage frequency outputs for every IE by each time phase
Successive Execution of Systems and ETs corresponding to Exact Plant Conditions

1. Set the exact equipments status
   - In-service, Standby or Out-Of-Service of PRA equipments

2. **Re-quantify the system failure probabilities** based on exact equipments status
   - the failure probability of maintenance equipment as 1.0
   - Based on BDD method using ARALIA

3. **Re-quantify Event Trees** using updated system failure probabilities
   - We developed quantification Engines and successively quantification system cooperated.
   - COSMOS-FP stored sets of status of equipments and the quantification results (CDFs for each IE and the sequences of CDF) to COSMOS-DB.
COSMOS-SD (for shutdown)

- **COSMOS-GUI**
  - Equipment Status (User Inputs)
  - POS Defining / COSMOS-SD (COSMOS AUTO.EXECUTE)
  - User Interface for Maintenance Schedule Inputting and calculated CDF Outputting for each POS / COSMOS-SD (COSMOS AUTO.EXECUTE)

- **COSMOS-DB**
  - Status of Equipments and Quantification results Storing

- **COSMOS QUANTIFICATION ENGINES and SYSTEMS**
  - ET Re-quantification ET ENGINE

- **SPLIT FRACTIONS**

- **Communications Control**

- **RISKMAN (OPENINSIGHT)**
  - PRA MODEL
  - (Using XML Format)
Key Features of COSMOS-SD

- COSMOS-SD is utilized for the risk evaluation during shutdown.
- Equipments are normally maintained each system units. So COSMOS-SD does not re-quantify FTs based on basic events but re-quantify only ETs based on systems.
- COSMOS-SD divides Shutdown into POSs automatically. Each POS is divided depending on RCS water level and the cooling systems (SG or RHR). Moreover they are divided by status of the mitigation systems.
Outage (Shutdown) Scheduling and Risk Evaluation (COSMOS-SD)

- **Input Generator**
  - Gantt Chart Operation
  - Inputs through Calendar
  - Inputs from Formatted file (XML)
  - “In-service” or “Standby“ or “Out-Of-Service” Switching

- **Result indication**
  - Time dependent CDF
  - The CDF sequence outputs by each POS
  - The core damage frequency outputs for every IE by each POS
Improvement RISKMAN model for Shutdown Evaluations

**RISKMAN MODEL**

- Initiating event: POS
- Top event: POS-1 duration time (hr)
- POS-2 duration time (hr)
- POS-3 duration time (hr)
- POS-4 duration time (hr)
- POS-5A duration time (hr)
- POS-5B duration time (hr)
- POS-5C duration time (hr)

**MULTI BRANCH POS ET**

**MAINTENANCE ET**

**SUPPORT and FRONTLINE ET**

- Top event: Reactor trip
- AFW
- HHSI
- Success
- Core damage

- Get all POSs CDF once quantification
- Maintenance System Status for Each POS
Demonstrations of COSMOS
5. Risk Monitoring Usages
At-power risk monitoring in case of OLM (COSMOS-FP)

- During the OLM, the risk significant system or component may be planned under the Out-Of-Service (OOS) condition. Thus when developing the OLM schedule, the plant must recognize the risk impact in every case of the possible configuration.
- Also during the actual OLM enforcement, the additional risk significant system or component can be accidentally failed. Thus, the plant must continuously evaluate the risk with the actual plant configuration during the OLM enforced period.
- In current Japanese status, the actual OLM enforcement has not been permitted in the plant maintenance application yet. However, utilities are steadily studying to introduce such activities for their plants with the risk monitoring system preparations.
At-power risk monitoring in case of OLM (COSMOS-FP) (cont.)

- The plant must evaluate the risk impact (CDF) by the possible OOS combination of risk significant system or component in the OLM planning stage. The plant can select the low-risk OOS combination form the risk information beforehand.
- COSMOS can easily evaluate this risk impact matrix for the OLM preparations.
At-power risk monitoring in case of OLM (COSMOS-SD)

- The shutdown PRA evaluations are applied as useful risk information for the outage scheduling optimization. Specifically, when developing the outage schedule, the risk mitigation measures were identified by analyzing risks to incorporate them into the outage schedule and so reduce risks during outage.
- To perform these activities, the risk monitoring system is effectively used.
- Also at the outage scheduling optimization, the plant sets the in-house risk criteria for the decision making.
At-power risk monitoring in case of OLM (COSMOS-SD) (cont.)

- If the plant risk level exceeds the in-house risk criteria, outage schedule should be modified. However, to achieve a balance with the other objective of PRA which is to improve efficiency, the outage schedule will be modified within a reasonably achievable range, and not all the risk mitigation measures will be reflected in the outage schedule.

- Even if risk exceeds the risk criteria and the outage schedule cannot be modified within a reasonably achievable range, the risk will be accepted with the following restrictions:
  - Greater attention to operation must be paid during the specified period with higher risk level.
  - Emergency measures must be confirmed beforehand during a period with higher risk level.
An example of the in-house risk criteria for the outage scheduling optimization.

For planned outage, there is some plant operating state that gravity injection or reflux cooling is not available.

For reference outage, there is no plant operating state that gravity injection or reflux cooling is not available.
An example of the flow of outage schedule optimization

1. Develop/modify planned outage
   - Agree with T-Spec?
     - Yes: Implement PRA for planned outage
     - No: CDF reduction is possible?
       - Yes: Outage settled with criteria
         - Call attention in high CDF period
         - Confirm on abnormal status in advance
       - No: Outage settled

2. Results is below in-house criteria?
   - No: Outage settled
   - Yes: Agree with T-Spec?
6. Further Enhancements of COSMOS
Further Enhancements for COSMOS

- GUI improvements for more user-friendly
- Event Tree (ET) quantification speeding-up more
- Importance calculation function adding
- Calculation logic of “COSMOS-SD” based on ETs re-quantification shifting to “COSMOS-FP” based on Fault Trees and ETs Re-quantification
- Linkage developing to the maintenance schedulers
- Deterministic evaluation (Defense-In-Depth) function adding
Conclusions

- “Risk Monitoring” is the essential item for the PRA usage and risk-informed activities, and we assume “At-power risk monitoring in case of On-Line Maintenance (OLM)” and “Shutdown risk evaluation for every outage” are 2 key issues for “Risk Monitoring”.

- Our company NEL has developed a Risk Monitoring System called COSMOS to support above 2 issues. COSMOS has two separated modules “COSMOS-FP” (for at-power) and “COSMOS-SD” (for shutdown) with the aim of each utilization.

- COSMOS-FP is utilized for at-power OLM scheduling. COSMOS-SD is utilized for the risk evaluation during shutdown period.

- COSMOS has been already the fundamental risk monitoring tool for the PRA usage and risk-informed activities. Also for the future applications for the risk monitoring and risk informed applications, COSMOS should continue to make the further enhancements.