Risk monitoring for nuclear power plant applications using Probabilistic Risk Assessment

KURAMOTO Takahiro

Design Service Division, Nuclear Engineering, Ltd., 1-3-7 Tosabori, Nishi-ku, Osaka 550-0001 Japan (tkuramoto@neltd.co.jp)

Abstract: Systematic and comprehensive Probabilistic Risk Assessment (PRA) is used to evaluate risks for Nuclear Power Plants (NPPs), and the risk information is also used to enhance the rationality and accountability of safety-related activities, and to realize efficient management in NPPs. Regulators and industry are discussing the standards and guidelines for the various types of PRA and management for near-future usage. "Risk Monitoring" is the essential item for PRA usage and risk-informed activities, and we assume "At-power risk monitoring in case of On-Line Maintenance" and "Shutdown risk evaluation for every outage" are two key issues for "Risk Monitoring". This paper describes the COSMOS Risk Monitoring system, and also of its usage for "At-power risk monitoring in case of On-Line Maintenance" and "Shutdown risk evaluation for every outage".

Keyword: Probabilistic Risk Assessment (PRA); risk monitoring; risk informed

1 Introduction

In conducting a Probabilistic Risk Assessment (hereafter "PRA") for a nuclear power plant (hereafter referred to as the "plant"), PRA models are created which can track the progress of an event by assessing the failure probability of plant components and operator actions in order to determine possible combinations of events causing plant anomalies and the frequencies of such events. The resultant plant condition depends on the successful or unsuccessful actuation of mitigating functions. Level 1 PRA performs a quantitative assessment on whether an event will lead to a condition where the function of removing heat from fuel becomes unavailable (hereafter referred to as "core damage") based on the probabilities of mechanical failure of components and human errors.

The results obtained by 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 the nuclear industry are 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 systems should be developed.

In many countries, risk monitoring has already been instigated for risk-informed applications consistent with PRA models. The status of such applications globally is described in the OECD/NEA report NEA/CSNI/R(2004)20[1].

Consequently, "Risk Monitoring" is the essential item for applying PRA and risk-informed activities, and "At-power risk monitoring in case of On-Line Maintenance" and "Shutdown risk evaluation for every outage" are two key issues for "Risk Monitoring".

COSMOS is a risk monitoring system developed by Nuclear Engineering Ltd. (hereafter "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.[2][3] COSMOS can provide complete linkage with the integrated PRA tool, RISKMAN, which has been widely adopted by plants worldwide. NEL is working on the development and improvement of COSMOS in cooperation with ABS Consulting, the developer of RISKMAN.

2 Characteristics of the risk monitoring System COSMOS

Conventional risk monitoring systems maintain core damage sequences, which were developed prior to operation utilizing PRA models intended for the risk

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monitoring system, and core damage frequencies are calculated based on the database. Therefore, conventional risk monitoring systems have disadvantages in that the plant components for which Out-Of-Service (OOS) conditions should be taken into account need to be identified in advance, and the accuracy of calculation largely depends on the developed database. On the other hand, COSMOS adopts a method of re-calculating core damage frequencies according to changes in the conditions, which enables the treatment of unavailability of all the components to be modeled. Accordingly, COSMOS can eliminate the necessity of developing PSA models specific to the risk monitoring system and identifying data such as core damage sequences in advance.

COSMOS is applicable to assessment during operation including the establishment of on-line maintenance plans and risk assessment in case of an occurrence of trouble. On the assumption of the unavailability of a component (component is OOS) it can determine core damage frequencies by recalculating the unavailability of the system concerned and tracking the accident sequence according to the unavailability of the component. It also automatically generates the database of calculated unavailability of the system containing a certain component, and thus shortens the time required for assessment.

For the shutdown mode assessment, in order to perform the assessment of risks during outage on a cyclic basis, COSMOS enables the assessment of the total outage process in a package by automatically setting the Plant Operating State (POS: the category of plant status based on the temperature, pressure, RCS level and other parameters, as an assumption for analysis) according to the entered outage process, and subdividing the POS according to the in-service or out-of-service status and operating conditions of a component in each outage configuration .

3 Detailed functions of COSMOS

COSMOS has two separate modules “COSMOS-FP” (for at-power) and “COSMOS-SD” (for shutdown).

COSMOS-FP is the system used for “At-power risk monitoring in case of On-Line Maintenance”, and COSMOS-SD is used for “Shutdown risk evaluation for every outage”.

The system composition of COSMOS is shown in Fig.1.

3.1 COSMOS-FP

3.1.1 On-line maintenance scheduling and risk evaluation

COSMOS-FP has the basic functions of a risk monitoring system - that is, maintenance schedule input and results indication. The main window of COSMOS-FP is shown in Fig.2.

(The maintenance Schedule Input function)

- Gantt Chart Operation
- Inputs through Calendar
- Inputs from Formatted file (XML)
- “In-service” or “Standby” or “OOS” Switching

(The results indication function)

- Time dependent core damage frequency (CDF) and/or ICCDP/Cumulative ICCDP Outputs
- The CDF sequence outputs by each time phase
- The CDF outputs for every Initiating Event (IE) by time phase

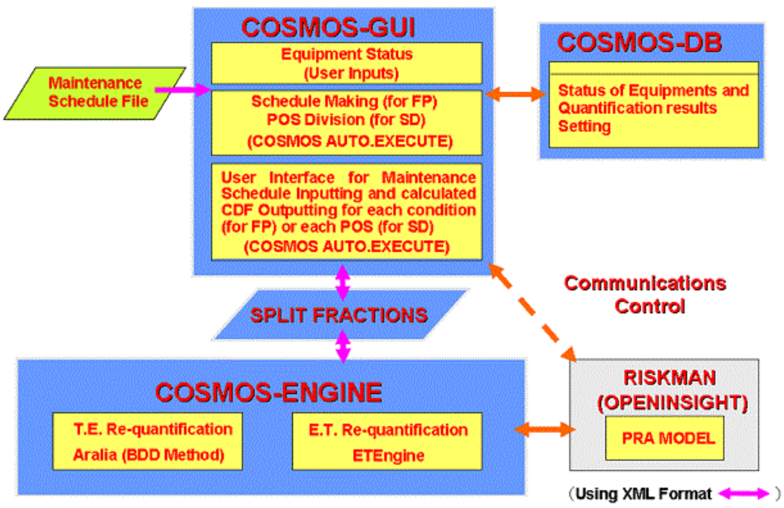

Fig.1 System composition of COSMOS.

Fig.2 Main window of COSMOS-FP.

3.1.2 For successive execution of systems and Event Trees (ETs) corresponding to exact plant conditions (in-service, standby or OOS of PSA equipment)

COSMOS-FP takes the equipment status (in-service, standby or OOS of PRA equipment) and re-quantifies the system failure probabilities concerning them. The maintenance equipment is not available in COSMOS-FP. COSMOS-FP re-quantifies the systems with an assumed failure probability of 1.0 for these items.

COSMOS-FP sets the failure probabilities of basic events corresponding to the maintenance equipment as 1.0, re-quantifies fault tree calculations for the top events by the Binary Decision Diagram (BDD) method using ARALIA on the affected event tree. Quantification engines and a successive quantification system was developed in cooperation with ARBoost Technologies.

Ultimately, COSMOS-FP does not require special PSA models for RMS and CDF sequences, so it is not necessary to pre-prepare a sequence or database.

3.1.3 For realization of speeding-up quantification

COSMOS-FP saves sets of status of equipment and the quantification results (CDFs for each IE and the sequences of CDF) quantified previously. If COSMOS-FP takes the status of equipment for a set that was quantified previously, it will not re-quantify any systems and indicates the results which were saved in the COSMOS_DB previously. Users can thereby save on computing time in quantification. COSMOS_DB is built in MS-ACCESS.

3.2 COSMOS-SD

3.2.1 For shutdown scheduling and risk evaluation

COSMOS-SD also has the basic functions of a risk monitoring system - that is, the outage schedule input and results indication similar to COSMOS-FP. The main window of COSMOS-FP is shown in Fig.3.

(The shutdown Schedule Input function)

- Gantt Chart Operation
- Input through Calendar
- Input from Formatted file (XML)
- “In-service” or “Standby” or “OOS” Switching

(The result indication function)

- Time dependent CDF
- The CDF sequence outputs by each POS
- The CDF outputs for every IE by each POS

COSMOS-SD divides the shutdown period into POSs. Each POS is divided by Reactor Coolant System (RCS) water level and the availability of the cooling systems such as Steam Generator (SG) or Residual Heat Removal System (RHRS). Moreover they are divided by the status of mitigation systems.

3.2.2 For improvement of a shutdown RISKMAN model to speed-up quantification for various POS status

The main purpose of shutdown risk evaluation is to grasp the total shutdown risk across the whole outage period. So the calculation logic of COSMOS-SD is different from COSMOS-FP. In shutdown, there are many plant configurations according to POS and maintenance status, so the RISKMAN model needs improvement to speed-up calculation.

Maintenance activities during shutdown are executed on each train in the systems involved in the maintenance. Basically, each train corresponds to an event heading. So when considering a specific train’s maintenance, we set to 1.0 the failure rate of the event heading corresponding to the train. The RISKMAN model considering such a treatment, defining sets of maintenance trains and the event heading was pre-prepared. COSMOS-SD can then treat such train maintenance correctly. So COSMOS-SD does not quantify any Fault Trees (FTs) and only quantifies ETs. Thus the quantification in COSMOS-SD is faster due to not carrying out costly FT re-quantification.

COSMOS-SD quantifies CDFs for each POS based on its period and COSMOS can quantify this all in one run at high speed.

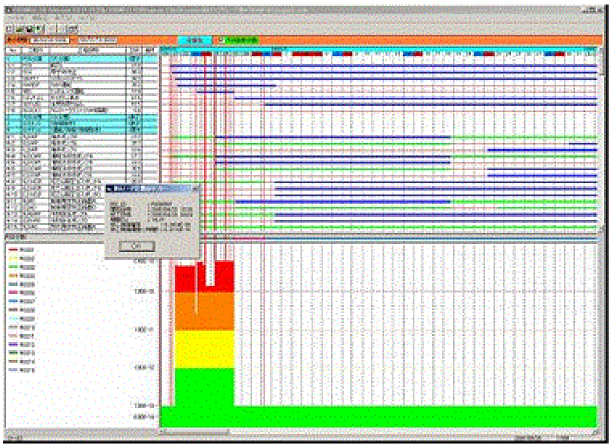

Fig.3 Main window of COSMOS-SD.

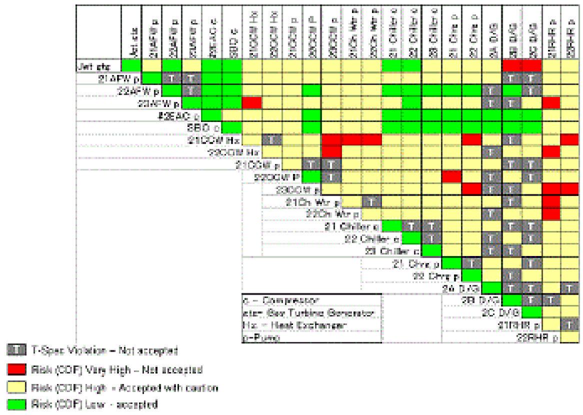

Fig.4 An Example of the risk impact of OLM combinations.

4 Risk monitoring usage

4.1 At-power risk monitoring in case of On-Line Maintenance (COSMOS-FP)

The at-power PRA evaluations are applied as useful risk information in case of On-Line Maintenance (OLM). During OLM, the risk significant system or component may be modeled under the OOS condition. Thus when developing the OLM schedule, the plant must recognize the risk impact in every possible configuration.

Also during the actual OLM enforcement, the additional risk significant system or component may accidentally fail. Thus, the plant must continuously evaluate the risk with the actual plant configuration during the OLM enforced period.

To perform these activities, the risk monitoring system must be used effectively. In Japan currently, actual OLM enforcement has not been permitted in plant maintenance applications yet. However, utilities are steadily studying to introduce such activities for their plants with the risk monitoring system preparations.

One important preparation for this activity is that the plant must evaluate the risk impact (CDF) by the possible OOS combination of risk significant systems or components in the OLM planning stage. The plant can select the low-risk OOS combination from the risk information beforehand.

Fig. 4 is an example of the risk impact of OOS combinations. COSMOS can easily evaluate this risk impact matrix for the OLM preparations.

4.2 Shutdown risk evaluation for every outage (COSMOS-SD)

The shutdown PRA evaluations are applied as useful risk information for outage scheduling optimization. Specifically, when developing the outage schedule, the risk mitigation measures are 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 must be used effectively. Also for outage scheduling optimization, the risk criteria are required for decision making.

The following is one actual example of this activity.

The main objectives of shutdown PRA are to improve efficiency by reducing the outage period, and to reduce the risks during outage. To achieve these objectives, the plant must autonomously develop a low-risk outage schedule. The plant sets the in-house risk criteria as acceptable risk levels to clarify the level of “shutdown safety” for each outage.

In setting the criteria, the plant referred to cases in the US regarding management goals and the CDF values for their own past outages. The in-house risk criteria (total CDF per outage and time based CDF per hour) were determined as shown in Fig. 5.

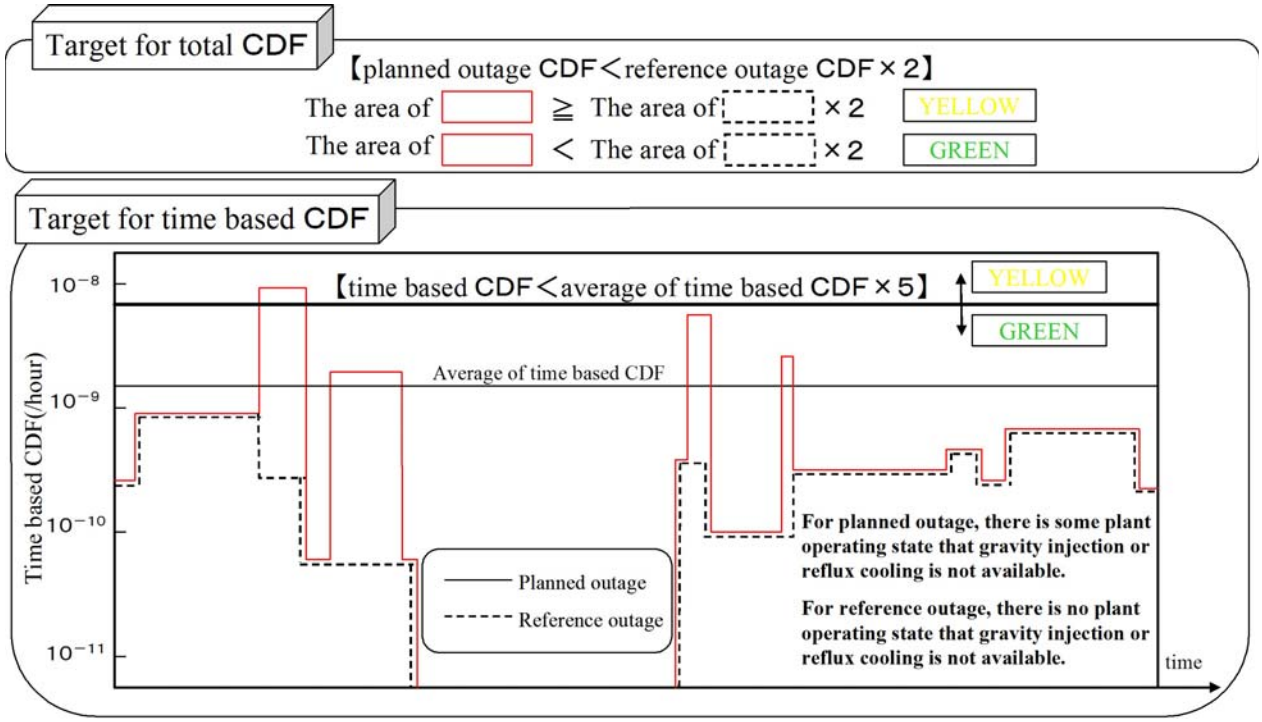

Fig.5 An example of the in-house risk criteria for the outage scheduling optimization.

The criteria shown above were chosen as the risk levels acceptable for the plant. If these were exceeded, the 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 (shown in Fig. 6). If risk exceeds the in-house risk management criteria but 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.

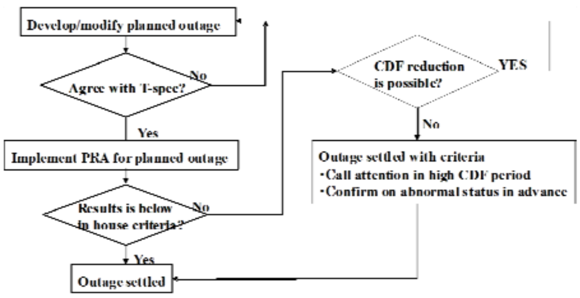

Fig.6 An example of the flow of outage schedule optimization.

5 Further enhancements of COSMOS

As described in section 2 through section 4, utilities are steadily studying the introduction of risk monitoring systems. NEL is also working on these activities by adopting COSMOS.

COSMOS is already a fundamental risk monitoring tool for the PRA as "At-power risk monitoring in case of On-Line Maintenance" and "Shutdown risk evaluation for every outage".

For future applications of risk monitoring and risk informed applications, the following further enhancements could be considered for COSMOS.

- Graphical User Interface (GUI) improvements for more user-friendly
- Event Tree (ET) quantification acceleration
- Addition of an importance calculation function
- Calculation logic of "COSMOS-SD" based on ET re-quantification shifting to "COSMOS-FP" based on Fault Trees and ET Re-quantification
- Developing the linkage with maintenance schedulers
- Addition of a deterministic evaluation of DID (Defense-In-Depth) function

6 Conclusion

In Japan, we are now paying much attention to risk-informed activities using PRA results. The regulatory agencies and industry are discussing standards and guidelines for various aspects of such activities for near-future application. "Risk Monitoring" is the essential item for 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 two key issues for "Risk Monitoring".

NEL has developed a Risk Monitoring System called COSMOS to support the above two issues.

COSMOS has two separated modules "COSMOS-FP" (for at-power) and "COSMOS-SD" (for shutdown).

COSMOS-FP is utilized for at-power OLM scheduling and has a feature of successive execution of systems and Event Trees corresponding to the OLM equipment. 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 possible configuration. Also, during the actual OLM enforcement, the additional risk significant systems or components can accidentally fail. COSMOS-FP is effectively used for the continuous risk evaluation of the actual plant configuration during the OLM enforced period.

COSMOS-SD is utilized for risk evaluation during a shutdown period. For shutdown, equipment is normally maintained by the system unit. So COSMOS-SD does not quantify Fault Trees, and only quantify ETs considering the system status at each configuration. The shutdown PRA evaluations are applied as useful risk information for outage scheduling optimization. Specifically, when developing the outage schedule, risk mitigation measures were identified by analyzing risks to incorporate them into the outage schedule and so reduce risks during outage.

COSMOS-SD may be effectively used for the outage scheduling optimization. To optimize decision making, the plant should have pre-defined risk criteria.

COSMOS is already a fundamental risk monitoring tool for PRA usage and risk-informed activities.

For future applications in the risk monitoring and risk informed applications, COSMOS should continue to make further enhancements.

Nomenclature

BDD	Binary Decision Diagram
CDF	Core damage frequency
DID	Defense-In-Depth
ET	Event tree
FT	Fault Trees
GUI	Graphical User Interface
IE	Initiating Event
NEL	Nuclear Engineering, Ltd
NPP	Nuclear Power Plants
OLM	On-Line Maintenance
OOS	Out-Of-Service
POS	Plant Operating State
PRA	Probabilistic Risk Asessment
RCS	Reactor Coolant System
RHRS	Residual Heat Removal System
SG	Steam Generator

References

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