The Implementation Standard for Internal Fire Probabilistic Risk Assessment of Nuclear Power Plants

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Abstract: Internal Fire PRA (IFPRA) is an analysis method which can quantitatively evaluate plant damage states, including core damage frequency. Because PRA results can be used for identifying the causes of end states, such as simultaneous multiple components failures (SMCF) of safety significant components induced by the effect of fire, by analyzing the results systematically, it is utilized worldwide.

Because the Implementation Standard for IFPRA has not yet been developed in Japan, Japanese utilities have not evaluated fire consequences sufficiently.

Considering the circumstances, the Atomic Energy Society of Japan (AESJ) has been working on development of the "Implementation Standard for Internal Fire Probabilistic Risk Assessment of Nuclear Power Plants" since fiscal year 2012. This IFPRA standard prescribes the requirements and specific methods to implement Level 1 PRA for accidents initiated by internal fire at NPPs during power operation.

This standard is being finished at the Fire PRA subcommittee under the Risk Technical Committee for the Standards Committee of AESJ, and is expected to be published in fiscal year 2014.

This standard will give great support to PRA engineers for performing the IFPRA with adequate quality, by identifying vulnerabilities associated with internal fire, and moreover will contribute to further improvement of the NPPs' safety.

Keywords: PRA, Internal Fire, AESJ Standard, Nuclear Power Plant

1. INTRODUCTION

The Standards Committee (SC) of Atomic Energy Society of Japan (AESJ) has been working on the preparation of the Internal Fire PRA (IFPRA) Standard since June 2012, at the Fire PRA Subcommittee set up under the Risk Technical Committee (RTC) for the SC. This IFPRA Standard is expected to be finished soon and be published in fiscal year 2014.

The IFPRA standard provides the guidance specifically for implementing internal fire Level 1 PRA to identify the accident sequences beginning with internal fire and leading to core damage, and to quantify these accident sequences during power operation of light water reactors. The requirements and the specific methods for conducting the IFPRA are established by taking into account opinions of experts in related areas.

As the issues to be addressed in establishing IFPRA Standard were already presented at the PSA2013 conference[1)], this paper focuses on the detailed contents of the IFPRA Standard.

2. APPLICABLE SCOPE OF THE IFPRA STANDARD

The IFPRA Standard prescribes the requirements and specific methods to implement Level 1 PRA for accidents initiated by internal fire at NPPs during power operation. This standard applies to only item (a) of Table 1 and does not apply to external events such as the items (b) and (c) shown in Table 1.

This Standard mainly focuses on thermal effects, and excludes other effects, such as component failure due to micro-particle of smoke and mechanical damage due to explosion, which could induce large uncertainty on Fire PRA results because of insufficient scientific knowledge for them.

Table 1 Categorization fire events

		Events which may cause fire	
		Internal Event	External Event
Fire Source Position	On-Site (Internal fire)	(a) Fire caused by failure of components and human errors during maintenance activities.	(b) Fire caused by on-site equipment damage induced by external events such as earthquakes.
	Off-Site (External fire)	—	(c)Fire occurred off-site induced by external events such as earthquakes, which spreads into the site.

3. DETAILS OF THE IFPRA STANDARD

3.1 Structure of the IFPRA Standard

This Standard is composed of the 12 chapters as follows, and the actual evaluation procedures are explained in the Chapters 5 through 12, as shown in Figure 1. Some results of each process will be fed back and reviewed, or some processes may be implemented in parallel.

(1) Scope and applicability

(2) Cited standards

(3) Glossary

(4) IFPRA procedure and assurance of quality

(5) Collection of plant information

(6) Analysis of plant information

(7) Screening of fire zones

(8) Developing fire scenarios for quantitative screening

(9) Screening of fire scenarios

(10) Developing fire scenarios for detailed analysis

(11) Quantification of accident sequences

(12) Documentation

The provisions are clearly described in both the text and the appendices (requirements). In addition, in the appendices (rules and references) and explanation, the actual evaluation examples and the applicable methods are provided to help users understand the provisions of the Standard as necessary.

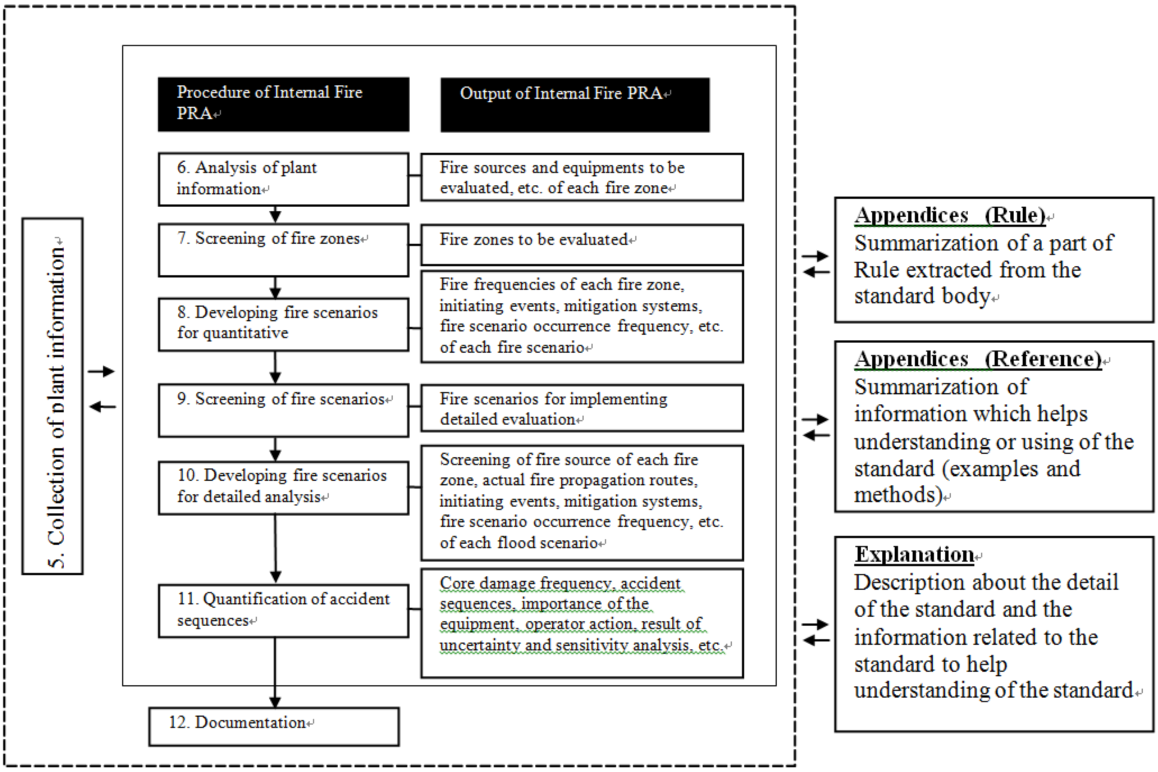

Figure 1: Implementation procedure of Internal Fire PRA

Details from Chapter 5 to Chapter 12 are shown in 3.2.

3.2 Requirements for Each Evaluation Step

3.2.1 Collection of plant information [Chapter 5]

1) Collection of information to implement IFPRA

Besides the information acquired by the internal event PRA, the information necessary for implementing the IFPRA should be collected from the plant drawings and specifications, domestic and overseas data for accidents and incidents etc. in order to figure out the characteristics of the fire source and the plant layout.

2) Plant walkdown

Plant walkdowns should be performed in order to acquire the “as-is” information which can be difficult to be confirmed from documents and are to confirm the validity of fire scenarios evaluated in the step of detailed analysis described in 3.2.6 [Chapter 10)].

Plant walkdowns should confirm boundary of fire zones, fire sources, installed locations of the equipment which may be affected by fire, and spatial allocation of the equipment in each fire zone.

3.2.2 Analysis of plant information [Chapter 6]

1) Definition of fire zones

The fire zones should be set based on the plant schematics etc. As a general rule, the establishment of the fire zones should be made by each building, and the following conditions should be considered.

- Existence of physical barriers (e.g. fire wall, fire barrier, bulkhead)
- Existence of openings (e.g. doors, equipment hatches)

- Spatial separation between installed locations of equipment

2) Identification of fire sources

The type, location and number of fire sources should be identified and they are sorted out by each fire zone.

3) Identification of the equipment which may be affected by the internal fire

The equipment, including cables and electronic devices, in each fire zone which may cause an initiating event(s) induced by malfunction or loss of its function due to internal fire should be identified. In addition, the mitigation systems which may malfunction or lose its function due to the effect of internal fire should be identified and associated with each fire zone.
Such information should be sorted out by the fire zone and a list should be developed for the purpose of management.

3.2.3 Screening of fire zones [Chapter 7]

Based on the information summarized in 3.2.2 [Chapter 6] regarding the fire source and affected equipment in each zone, the fire zones are screened to select the zones which will be considered in a fire scenario as described in the section 3.2.4 [Chapter 8], and those zones which can be excluded from the following viewpoints:

- If there is no fire source in the zone and there is no fire propagation from the adjacent fire zone, the fire zone is excluded.
- If there is a fire source in the zone but there is no equipment which is identified in the section 3.2.2. 3) [Chapter 6], the fire zone is excluded only if there is no fire propagation from the specified fire zone to other zones.

3.2.4 Developing fire scenarios for quantitative screening [Chapter 8]

Figure 2 shows the correlation diagram between Chapter 8 and other Chapters 6, 7, 9 and 10.

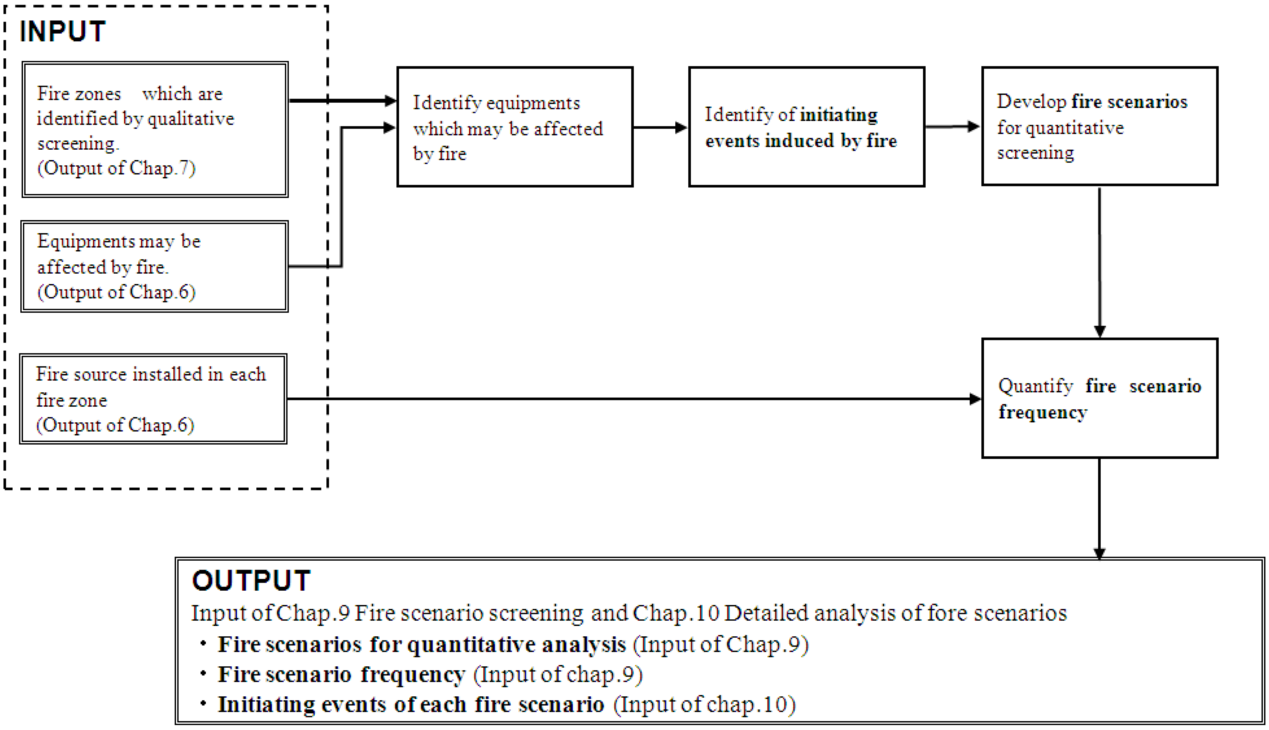

Figure 2: Correlation Diagram between Chapter 8 and Chapters 6, 7, 9 and 10

1) Identification of equipment which may be affected by internal fire

The fire scenarios should be developed under conservative assumptions in which all equipment installed in the specified fire zone that are not excluded in the section3.2.3 [Chapter 7] malfunction or lose its function due to internal fire, and the frequency of each scenario is quantified in setting fire scenarios for quantitative screening.

Not only single-zone fire scenarios in which the fire affects only the specified fire zone, but also multi-zone fire scenarios in which the fire propagates from the specified fire zone to other zones, should be identified. Multi-zone fire scenarios are identified by combining the fire initiation zone and fire spread zone, and identifying the fire spread routes and their characteristics.

On the other hand, the main control room (MCR) is excluded from the subjects of quantitative screening and the fire scenarios including MCR should be set in 3.2.6. 7) [Chapter 10] “Identification of fire scenarios for detailed analysis”, because control panels which are essential for plant shutdown operation are installed in MCR, and thus the fire zone which includes MCR is of particular importance.

a) Single-zone fire scenario

Based on the equipment and cable list which were arranged in 3.2.2.3) [Chapter 6] in association with the fire zone, the equipment and cables affected by fire and equipment associated with cables which are damaged by fire should be identified and associated with each fire zone.

b) Multi-zone fire scenario

b-1) Identification of the combinations of fire initiation zone and fire spread zone

Combinations of the fire initiation zone and fire spread zone should be identified. For multi-zone fire scenarios, propagating routes should be identified according to each combination.

b-2) Qualitative screening of the combination of fire zones

The following criteria should screen out fire zones from those identified in 3.2.4.1) b-1) [Chapter 8].

- There is no equipment or cable that is affected by fire in the fire spread zone.
- There is no difference in the fire effects on the plant between the fire initiation zone and fire spread zone.

b-3) Identification of equipment which is affected by internal fire

Like single zone fire scenarios, based on the equipment and cable list which was arranged in association with the fire zone in 3.2.2.3) [Chapter 6], the equipment and cables affected by fire and equipment related to cables which are damaged by fire should be identified and associated with each combination of fire zones.

2) Identification of initiating events induced by fire

Based on the results of 3.2.2.3) [Chapter 6] and 3.2.4.1) [Chapter 8], initiating events which are induced by fire should be identified associated with each fire scenario without any exception.

3) Development of fire scenarios for quantitative screening

Based on the results of the section 3.2.2.3) [Chapter 6] and 3.2.4.1) [Chapter 8], fire scenarios which are characterized by mitigation systems affected by fire and initiating events induced by internal fire should be developed.

4) Quantification of fire scenario frequencies

The frequencies of fire scenarios for quantitative screening should be calculated by following steps. Any other conservative fire scenario frequencies can be used provided that its applicability can be justified.

a) Quantification of fire frequencies by each fire source

When the fire frequency and uncertainty of each fire source are to be calculated initially, the "Implementation Standard Concerning the Estimation of Parameters for Probabilistic Safety Assessment of Nuclear Power Plants" [2)] should be applied for the calculation, and the calculated results are used as the database of the fire frequency.

When an existing database of fire frequency is used directly, or when the Bayesian method is applied to an existing database of fire frequency as prior distribution, it is necessary to confirm that the database has sufficient supporting data and is consistent well with the characteristics of the plant subject to the evaluation.

Database other than the nuclear industry can be applied for the fire sources for which information available from the nuclear industry is not sufficient, if its applicability can be justified.

b) Quantification of fire frequencies of fire zones

Based on the database of fire frequencies, the fire frequency of each fire zone should be quantified.

If multiple fire sources exist in the same fire zone, the cumulative fire frequencies of individual fire sources represent the fire frequency of the fire zone.

c) Quantification of fire scenario frequencies

Based on the fire frequency of the fire zone calculated in 3.2.4.4).b) [Chapter 8], fire scenario frequencies should be quantified.

Based on the fire scenarios developed in 3.2.4.3) [Chapter 8], quantitative screening can be preformed under a conservative assumption, for example, all equipment installed in the fire zone affected by fire will be damaged, and fire suppression by operators cannot be expected.

3.2.5 Screening of fire scenarios [Chapter 9]

Figure 3 shows the correlation diagram between Chapter 9 and other Chapters 5, 6, 8, 10 and 11.

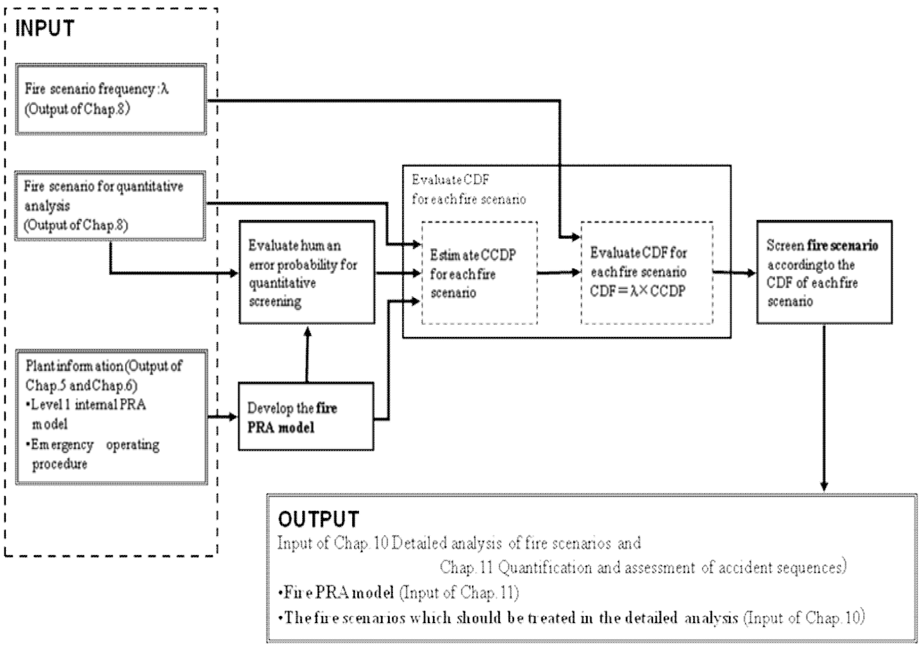

Figure 3: Correlation Diagram between Chapter 9 and Chapters 5, 6, 8, 10 and 11

1) Quantitative screening of fire scenarios

The core damage frequency (CDF) of each fire scenario should be calculated by using the fire model for quantifying the Conditional Core Damage Probability (CCDP) of each fire scenario developed in the section 3.2.4.3) [Chapter 8] and setting screening value of Human Error Probability (HEP) for each fire scenario. The quantitative screening is preformed under a conservative assumption that fire suppression by operators cannot be expected. As described in 3.2.4 [Chapter 8], MCR is excluded from the subject of quantitative screening because MCR is obviously an important fire zone.

2) Development of fire PRA models

Based on internal PRA model, the fire PRA models for quantification of CCDP of fire should be developed by identifying the equipment, failure modes, and their effects to be considered in the fire PRA model.

a) Review of internal PRA Models

Based on the review of internal PRA models, the accident sequence including associated equipments of fire sequence and those failure modes that must be added to or excluded from fire PRA models are identified. Fire PRA models should be developed by incorporating the result into internal PRA models.

b) Incorporation of equipment failure induced by fire into fire PRA models

For the purpose of evaluating fire effects on the equipment identified in 3.2.2.3) [Chapter 6], equipment failure induced by fire should be identified and incorporated into fire PRA models.

c) Incorporation of human error events induced by fire into fire PRA models

Human error events which are not included in internal PRA models and those specific to fire should be identified and incorporated into fire PRA models developed in 3.2.5.2)a) [Chapter 9]. Identification of the human error events and setting of the screening value of human error probability are described in 3.2.5.3) [Chapter 9] “Estimation of human error probability for quantitative screening”

3) Estimation of human error probability for quantitative screening

Human error events which occur in the fire scenario are identified. The screening value of HEP for the human error event identified is set.

a) Identification of human error events

The applicability of the human error events which are modeled in internal PRA models is confirmed by reviewing internal PRA models. The human error events which must be modeled in fire PRA models should be determined by identifying human error events specific to fire considering the operational procedures associated with fire.

b) Human error probability in the quantitative screening

The screening value of human error probabilities for the human error events which are identified in 3.2.5.3.a) should be set for each fire scenario.

4) Evaluation of core damage frequency of fire scenarios

The CDF of each fire scenario should be determined by multiplying CCDP of each fire scenario which has been quantified using fire PRA models developed in 3.2.5.2) [Chapter 9]and the screening value of human error probability rate set in 3.2.5.3) [Chapter 9] by the fire scenario frequency calculated in 3.2.4.4) [Chapter 8].

5) Fire scenario screening according to the CDF of each fire scenario

Fire scenarios which are to be evaluated in the detailed analysis should be identified based on the result obtained from 3.2.5.1) through 3.2.5.4) [Chapter 9] and the appropriate screening criterion set in this section.

3.2.6 Developing fire scenarios for detailed analysis [Chapter 10]

Figure 4 shows the correlation diagram between Chapter 10 and other Chapters 8, 9 and 11.

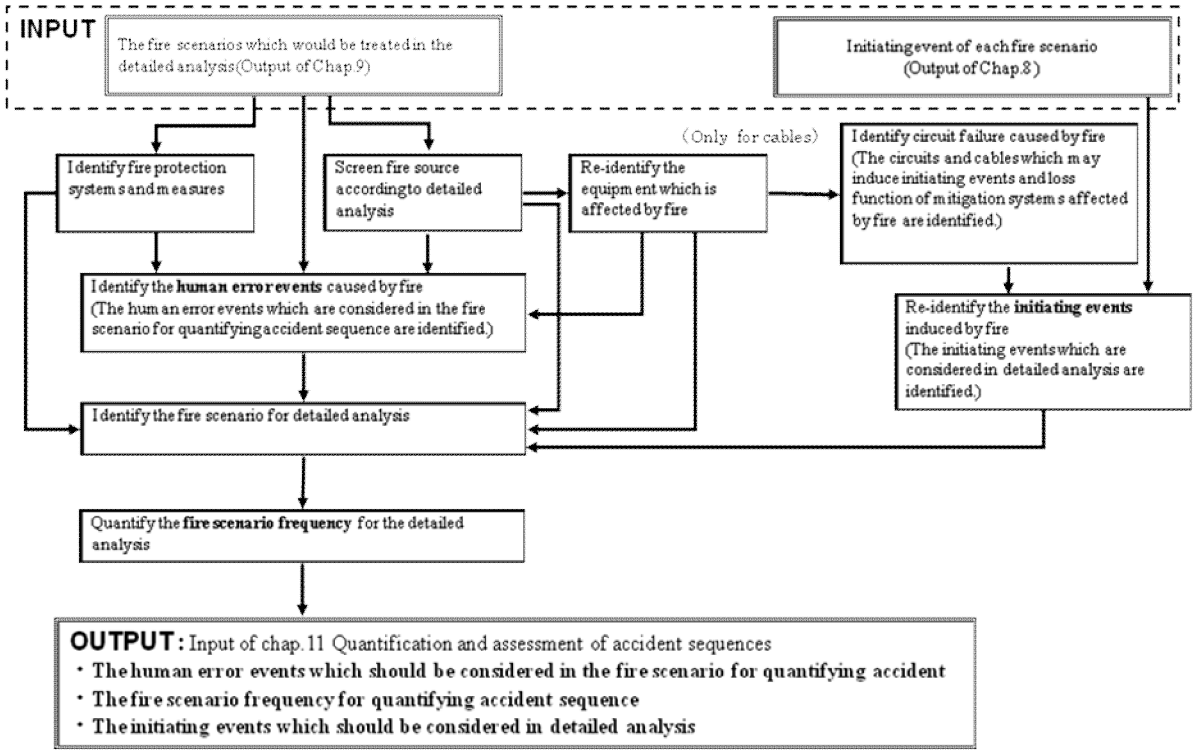

Figure 4: Correlation Diagram between Chapter 10 and Chapters 8, 9 and 11

1) Identification of fire protection systems and measures

The fire protection systems and measures which have the ability of prevention or suppression of fire growth and spread are identified for each fire scenario. When the prevention of fire spread by means of fire detectors and fire suppression systems are assumed, unavailability of all the fire suppression systems should be considered. Plant walkdowns should be performed in addition to the analysis of plant drawings and specifications depending on the degree of the detail of the analysis and availability of information.

1) Fire source screening by detailed analysis

Zone of influence (ZOI) should be estimated for each fire source in the specified fire zone.

When ZOI is estimated by using a fire model or an analysis tool, the applicability of the fire model or tool must be validated.

Also the effect of hot gas layer is considered in the estimation of ZOI. For estimation of ZOI, following information is necessary in addition to the information obtained in 3.2.5.1) [Chapter 9].

- Layout of equipment in each fire zone
- Specification of fire zone (e.g. height of ceiling)

- Fire model using estimation for damaged (ignited) distance
- Heat release rate of fire source
- Damage and ignition temperature of target equipment
- Status of ventilation and air-conditioning system (e.g. capacity, in operational status (in service or out of service))
- Existence of secondary fire sources

A fire scenario can be excluded from subsequent evaluations, if it is possible to demonstrate that a part of the safety equipment, which was conservatively assumed to lose its function in the section 3.2.5 [Chapter 9], will not lose its function due to fire.

The evaluation is performed on all the fire zones which contain associated equipments or are affected by fire. Similarly the fire scenarios which affect multiple fire zones should be also evaluated.

3) Re-identification of the equipment which is affected by fire

The fire scenario identified in 3.2.4.3) [Chapter 8] is developed under conservative assumptions. In order to perform more realistic analysis, the equipment determined to be affected by fire as described in 3.2.4.1) [Chapter 8] should be re-evaluated based on the results of 3.2.6.2) [Chapter 10].

If the equipment which is affected by fire depends on the success or failure of the equipment or the measures identified in 3.2.6.1) [Chapter 10], the equipment which is affected by fire should be identified according to the success or failure of the individual equipment and measure.

4) Identification of circuit failure caused by fire

Of the circuits and cables identified in 3.2.4.1) [Chapter 8], the circuits and cables which may induce initiating events potentially affected by fire should be identified. Initiating events frequencies may be estimated by circuit analysis. When circuit analysis is performed, circuit failure modes and response of equipment against circuit failure which are plant specific should be taken into account.

5) Identification of human error events caused by fire

Based on the fire scenarios identified in 3.2.5 [Chapter 9], human error events which may occur following fire should be identified. An investigation of the practicability of operator actions is carried out not only by collecting relevant documents, such as plant operating procedures (e.g. operating procedures for each equipment, emergency operating procedures, surveillance procedures, etc), but also by conducting interviews with operators and plant walkdowns. In addition, in order to identify the human error events which should be modeled in fire PRA models, human error events of internal PRA models are analyzed. If necessary, human error events specific to fire are incorporated into the fire PRA model.

6) Re-identification of the initiating events induced by fire

The fire scenarios identified in 3.2.4.3) [Chapter 8] are conservative. In order to perform a more realistic analysis, the initiating events identified in 3.2.4.3) [Chapter 8] should be re-evaluated based on the result of 3.2.6.2), 3.2.6.3), 3.2.6.4), and 3.2.6.5) [Chapter 10], according to the initiating events selected in 3.2.5) [Chapter 9] assuming that the same initiating event occurs, another initiating event occurs, or no initiating event occurs.

If the same initiating event occurs, the identification of fire scenarios described in 3.2.6.7)[Chapter 10] is performed on initiating events decided in 3.2.4.2) [Chapter 8]. If another initiating event caused by malfunction of equipment due to circuit failure affected by fire occurs, those new initiating events should be added to the fire PRA model. If multiple new initiating events occur simultaneously, the initiating event which will lead to the severest end state may represent all the events. If no initiating event occurs in the fire scenario, the concerned fire scenario can be excluded from the subsequent evaluations.

7) Identification of fire scenarios for detailed analysis

Comprehensively evaluating the results of 3.2.6.1), 3.2.6.2), 3.2.6.3), 3.2.6.4), 3.2.6.5) and 3.2.6.6) [Chapter 10], the fire sources in the fire zones which are subject to the detailed analysis, the initiating events and the effects on the mitigation system should be described as a fire scenario, and the fire scenario for the detailed analysis should be identified. The fire scenario concerning fire associated with MCR and alternative operations after the evacuation from MCR are also identified. Even if fire sources are different, the fire scenarios having similar initiating events and equivalent effect on the mitigation systems may be grouped into the same fire scenario.

If uncertainty analysis described in 3.2.7.4) [Chapter 11] is necessary, the uncertainty factors contained in the scenario should be identified. The mean value, the shape of probability distribution, and the width of uncertainty of important parameters, which were used in modeling the fire scenario should be indicated.

8) Quantification of the fire scenario for detailed analysis

The frequency of the fire scenario for the detailed analysis, which was identified in 3.2.6.7) [Chapter 10] should be calculated by multiplying the fire scenario frequency by the factor representing the characteristics of the fire scenario, such as severity factor which is defined as product of heat release rate and human error probability of fire suppression.

3.2.6 Quantification of accident sequences [Chapter 11]

Figure 5 shows the correlation diagram between Chapter 11 and Chapters 9 and 10.

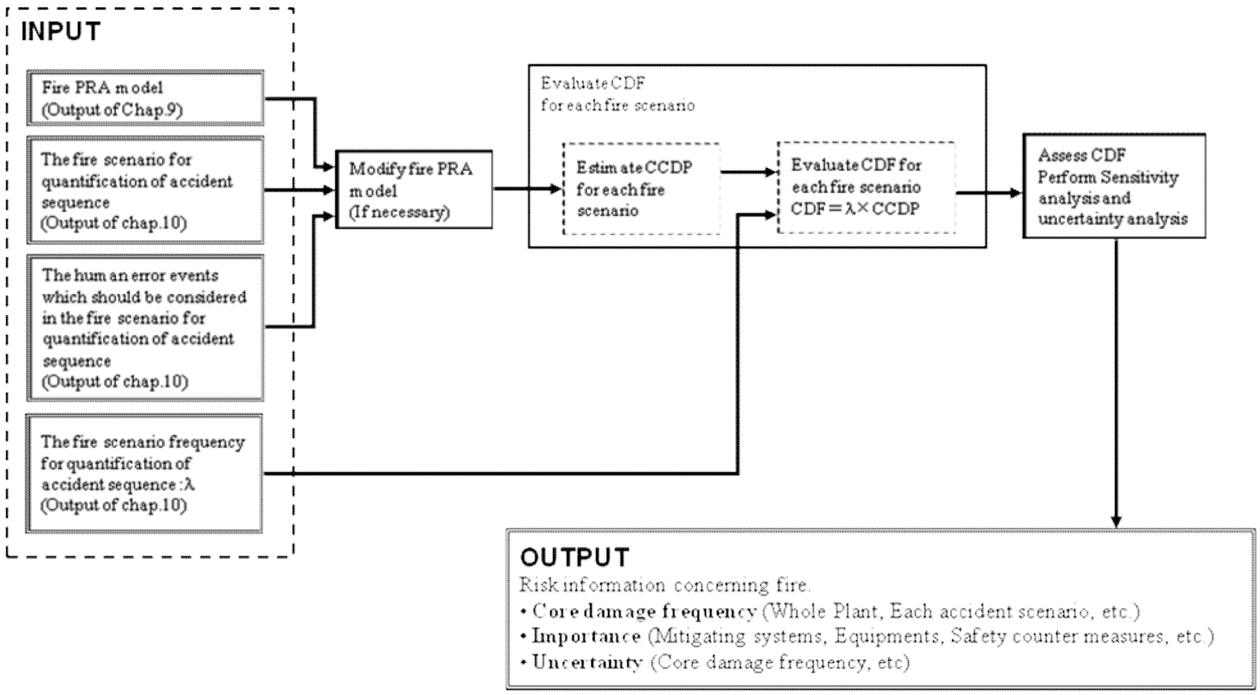

Figure 5: Correlation Diagram between Chapter 11 and Chapters 9 and 10

1) Evaluation of core damage frequency

A PRA model (event trees and fault trees) which is appropriate for the detailed analysis of the fire scenario determined in 3.2.6 [Chapter 10] should be developed and the core damage frequencies should be calculated by the point-estimate analysis.

It should be confirmed that the screening criterion for quantitative screening set 3.2.5 [Chapter 9] should be negligible compared with the core damage frequency as calculated above. If it is not negligible, the screening criterion for the quantitative screening should be lowered and re-evaluation of the fire scenario should be performed.

2) Importance analysis

An importance analysis should be performed to acquire useful quantitative information applicable to PRA such as factors which are dominant in the core damage frequency. For this importance analysis, the importance indexes are calculated. These include the factors causing the fire scenario, which significantly affects the core damage frequency (e.g. probability of failure of fire suppression), the random failure probability of the mitigation system for the accident sequence, and the probability of failure in taking mitigating actions against the accident sequence. Proposed importance indexes include Risk Reduction Worth and Fussell-Vesely Importance. An appropriate indicator should be selected according to the purpose.

3) Sensitivity analysis

Among the elements constituting the PRA, for those with relatively significant uncertainties, the sensitivity analysis should be conducted to confirm the effect of changes in these elements on the result. In addition, if the combination of multiple elements is considered to cause significant effects, a sensitivity analysis should be implemented on such a combination.

Assumptions, models, data and other factors that may cause a significant effect on the evaluation result should be selected as the subject of sensitivity analysis.

4) Uncertainty analysis

Based on the result of 3.2.7.1), 2.3.7.2) and 3.2.7.3) [Chapter 11], regarding the important parameters among the uncertainty parameters which affect the CDF, the uncertainty (e.g. the shape of probabilistic distribution) should be set for each parameter followed by propagation of the uncertainty to perform uncertainty analysis in order to determine the mean value of the CDF and the probability distribution (or the width of uncertainty). The uncertainty analysis may be omitted depending on the purpose of evaluation.

In performing the uncertainty analysis, the Monte Carlo method or other equivalent uncertainty propagation analysis methods can be applied to various uncertainty parameters to determine the mean value of the evaluation results and the width of the uncertainty depending on the purpose of evaluation. If no general method for setting the uncertainty width is available, a sensitivity analysis described in the section 3.2.7.3) should be performed to confirm the effect of uncertainty caused by changes in the elements constituting the PRA.

If there are too many scenarios to perform individual uncertainty analyses, an appropriate screening criterion is set according to the purpose of evaluation, and the fire scenarios not meeting this criterion may be excluded.

3.2.7 Documentation [Chapter 12]

The purposes, scope of evaluation, applied methods, conditions or assumptions, models, parameters and the results of fire PRA should be documented so that the details of PRA can be easily understood when IFPRA results are used and updated, and review by the experts should be conducted.

In addition, the utilization of expert judgments, the implementation of peer reviews, and the documentation of quality assurance reviews should be conducted.

4. CONCLUSION

Requirements and specific methods for performing an internal fire Level 1 Probabilistic Risk Assessment (PRA) among the PRA for light water reactors at power operation are being discussed by the fire PRA subcommittee consisting of experts in the related areas under the Risk Technical Committee for the Standards Committee of the Atomic Energy Society of Japan. The results of the discussion have been incorporated into the implementation standard of IFPRA which is expected to be published in 2014 fiscal year.

This standard will contribute greatly to PRA engineers for performing the IFPRA with adequate quality, identifying vulnerability concerning internal fire, moreover will contribute to further improvement of the NPPs' safety.

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References

[1] Toshiyuki Takagi, Katsunori Ogura, Naoyuki Murata, Development of the Implementation Standard for Internal Fire Probabilistic Risk Assessment of Nuclear Power Plants, *Proceedings of International Topical Meeting on Probabilistic Safety Assessment and Analysis (PSA 2013), September 22-27, 2013, p. 39*

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