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Study on the Fire Hazard and Risk Analysis Derived from the Plant Configuration Change During the Shutdown Period at Nuclear Power Plants

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Abstract

Fire hazard and risk analysis at Nuclear Power Plants is implemented on the basis of the normal operational configuration. This steady configuration, however, can be changed due to the temporary displacement of equipment, electric cable and irregular movement of workers through the fire compartments when the on-line maintenance is processed during the power operation mode or the scheduled outage mode for the refueling. With the consequence of this configuration change, the fire analysis condition and the evaluation result will be different from those that were analyzed based on the steady configuration. In this context, at this paper, the general items for the reassessment are categorized when the configuration has changed. The contemporary zone models for the detail fire analysis are also illustrated for their application for each classified condition.

Key Words : fire hazard analysis, configuration, fire modeling, CFAST

1. Introduction

The initially issued fire protection regulation for the operating nuclear power plants is GDC-3(General Design Criteria 3) of the Appendix A to 10CFR50[1]. This requirement, which is not so much different from the general fire protection design criteria for the industrial fields, has been applied to the safety-related structure, system and component at the commercial nuclear power plants from the early 1960s. However, with the experience of the fire incident at the Browns Ferry Nuclear Power Plant in March, 1975, which caused the damage of cable and safety-related components with safety attention to the public, the nuclear industry and regulatory body strongly felt the need to strength the design requirement and regulatory guideline for the fire protection program and its capabilities at the existing nuclear power plants.

As executable measures following to this need, BTP 9.5-1 and appendix A to 10CFR50 were published in 1976. Consecutively, appendix R to 10CFR50[2] and 10CFR50.48[2] that specify the fire protection program and the kernel of relevant regulations were enacted in 1979. In addition, with the publication of 10CFR50.12, 10CFR50.59 and several Generic Letters, the nuclear fire protection regulation incorporated the concept of defense-in-depth and the performance criteria as a full-fledged conservative requirement. In this consequence, the nuclear fire protection regulation came to hold different application features and peculiar characteristics compared to those of the regulation and requirement for the general industrial world. The fire protection regulation and guidelines for the nuclear industry had to reflect the availability and reliability of the facilities from the initial design stage with the purpose to secure the reactor safety and satisfy the design goal for the core damage frequency and the limitation of the allowable release of radioactive material to the external boundary. With this approach basically, the appraisal of fire incidents and application of fire frequency were estimated too conservative as a whole. This tendency was sustained to the implementation of prescriptive or deterministic regulation with the conservative approach in mind considering the uncertainties of the parameters and ambiguous situations.

Now, it came to be possible to interpret the ambiguous scopes and uncertain parts of the major parameters by use of the engineering experience and accumulated database from the increase of reactor year. Recently, a new technical approach was introduced to the discipline of the reactor safety which is the technique of probabilistic safety assessment for the evaluation of reactor safety quantitatively. This technique is also available to the fire protection field with alignment of the performance-based approach. The regulatory body and the nuclear industry in U.S. took collaborate efforts to prepare the performance-based regulatory ways concurrently with the existing prescriptive regulation. As an achievement of this effort, NFPA-805 that is the performance-based fire protection standard to secure the safety of the nuclear plants and enhance the practical capability and performance of the fire protection features, inaugurated in January, 2002 and promulgated in February, 2002. At present, NRC, the nuclear regulatory body in America, is under the activities of the rule-making and prepares the applicable guidelines for the NFPA-805 fire protection standard. It is estimated that the executable guidelines for this activities will be presented sooner or later this year.

NFPA-805 is the performance-based fire protection standard pursuing the successful result based on the realistic performance criteria together with the deterministic provisions of the prescriptive regulation. This standard deals with the fire protection activities at power-operation period and extends its application to the shutdown period of the plant outage. Particularly, this standard specifies the requirement of the fire protection facility and its features with a view to plant risk and safe shutdown capability. It also contains provisions for the continuous performance monitoring, even if the fire protection system and its facilities are not included in the scope of (b) at maintenance rule. In this consideration, this paper shows the analysis results as well as the review items for the fire risk and hazard derived from the plant configuration changes for shutdown, whose requirement is not obvious at present provisions or regulation.

2. The Evaluation of Fire Hazard Analysis and Safe Shutdown Capability at NPPs

2.1. Evaluation Items for Fire Hazard Analysis

The purpose of fire hazard analysis that is implemented and continuously required at most of the nuclear power plants, is to evaluate the safe shutdown functions of the power-operating plants at the time of fire occurrence by use of protective facilities and the operators' capabilities to cope with the accidents. The professional team evaluates the realistic protection ways to confine and limit the external release of the radioactive material at fire and verify that such functioning is secured at the plants. When it is compared for the fire safety evaluation between the power-operating plant and the shutdown period of plant, the same level of safety evaluation has to be performed for the period of plant shutdown to sustain the reactivity control, residual heat removal, spent fuel pool cooling, and other safety functions. The irradiation effect to the public has to be assessed under the same concept with that at power operation.

The items and relevant functions for the fire hazard analysis during the period of the power operation and the plant shutdown are comprehensively identical, whereas the input condition and the resulting status during the period of plant shutdown can be varied due to the plant configuration change. That is to say, fire protection areas can be changed or compartmentation among fire areas can be ambiguous at the time of on-line maintenance during power operation or at the scheduled maintenance period for the plant reshuffling. At this time, it is possible for the unexpected transient combustibles scattered around the workplace and the number of ignition sources and their positions can be uncontrollable. If the plant configurations differ from the design conditions or plant operating status, the fire hazard analysis for the changed fire area or compartment has to be reassessed. As a matter of course, this philosophy is duly acceptable when reflecting the defense-in-depth concept of fire, that is, taking the preventive action before fire occurrence, detecting the fire and suppression of the fire immediately and security of the essential safety functions. In this regard, the items for the general fire hazard analysis that should be evaluated whenever the plant configuration has changed were categorized on the basis of their characteristics.

1) Fire area or compartment and fire barrier at the plant location
   - geometric configuration and physical arrangement at each fire area or compartment
   - material characteristics such as fire resistance rating
   - compartmentation of the fire area and the fire spreading characteristics
2) Physical arrangement of facilities and structure, and the location of fire protection facilities and their application
   - facilities and structural displacement inside the fire area
   - the location and position of the fire detection, annunciation, fire suppression system and their availability
3) Code, standard and design guidelines[5] for fire prevention and protection
   - national code and standard applied by the original designers
   - regulations and characteristics of design guideline on effective date of license
4) Quantity, arrangement and combustion features of fixed and transient combustibles
   - fire load and severity
   - duration of fire and temperature-time distribution curve
   - chemical features of combustion products, toxicity, corrosiveness
5) Appropriateness of water reservoir, fire suppression system, and smoke removal system
   - water storage tank, water supply capacity and arrangement of main supply line
   - path for fire control and suppression, arrangement and interlock function of smoke control system
6) lighting, communication, electric power, and

supporting functions
- emergency lighting and communicative facilities for emergency egress and fire fighting control
- facilities and their demand capacity for the standby or emergency power
- availability of at-site and outside fire brigade and special functions of fire suppression equipment

7) Requirements of plant internal procedure and fire protection program
8) Periodic fire hazard analysis and review items according to the relevant National law and rules

2.2. Evaluation Items for Safe Shutdown Capability at NPPs

General items of evaluation for fire hazard analysis at nuclear power plants or industrial world are not so much different from items of original configuration compared to the changed status of configuration. On the other hand, in case of nuclear power plant's fire risk evaluation, safe shutdown capability and safety margin are importantly managed and regulatively controlled items at each operating modes in order to stabilize the nuclear reactor for hot shutdown, cold shutdown and guaranteed shutdown function.

Related with the nuclear power plant's fire protection, the capability to safely shutdown the reactor is requested even under the situation of fire following to the relevant codes and regulative guidelines. From the specific requirements of appendix A and R to 10CFR50 and 10CFR50.48 as well as the regulatory policy and guidelines, there is no exception to avoid the requirements to keep the capability of safe shutdown and to sustain the safety status. The major goal of this requirements is to control the reactivity of the reactor, inventory control of the primary coolant system, removal of decay heat or residual heat that are related with primary side shutdown capability. In this aspect, the evaluation items for safe shutdown capability during the process of reactor shutdown were divided in relation with the fire condition.

1) Design criteria of the safety related structure, system and equipment
   - possibility of fire or explosion and minimization of their effect
   - relationship and consistency of the function and capability for the structure, system and equipment
2) Fire protection characteristics of structure, system and equipment to ensure the safe shutdown capability
   - physical arrangement and barriers to assure the redundant, diversified and independent functions
   - availability and capability of main control room or emergency control area
   - analysis for the fire protection zone or area that is required for the independent or alternative safe shutdown capability
3) Material characteristics and required fire resistant rating for the major fire protection area
   - Usage of non-combustible or fire resistant material at fire area or compartment
   - required fire resistant rating and isolation features for each fire area or compartment
4) Safety-related cable and circuits, and non-safety related cable and power line associated with safety functions
   - ensuring safety for cable, electric circuit of the redundant train for the safety shutdown
   - possibility of hot short, open circuit and short to ground and the analysis for the spurious actuation with countermeasures
5) Active fire protection system, emergency lighting facility and passive fire protection capabilities

- capability of fire protection system and facilities ensuring safety function and their effects from real actuation
- physical supporting capability for the operator's habitability and fire fighting activities

6) Establishment of fire protection program and periodic fire hazard analysis for the operating power plants
   - establishment and implementation of fire protection program followed by the code and guidelines for the license agreement
   - periodic fire hazard analysis with the aid of qualitative and quantitative methodology

3. Evaluation of Fire Hazard Analysis from the Configuration Change During the Shutdown Period

3.1. Evaluation Items for Fire Hazard Analysis

10CFR60.65 that is regulative requirement to evaluate and monitor the effectiveness of the maintenance at nuclear power plant, is often called as Maintenance Rule. While the nuclear power plant's fire protection system and equipment are not within the scope of maintenance rule, the monitoring of the impact from the plant configuration change has to be processed to evaluate the fire hazard analysis and safe shutdown capability based on the fire related codes and standards. In this aspect, this study addressed to the changeable items from the viewpoint of the fire hazard and risk to prepare for the requirement of the (a)(4) of the maintenance rule, which requests that before performing maintenance activities the risk increase from the proposed maintenance activities must be assessed and managed. These days in U.S. or technically advanced countries, the ways to evaluate the fire risk and hazard during the scheduled outage period has been issued as a concerning subject. Now, to deal with this argument, experts at the nuclear power industry are developing a specific plan for the application of performance-based fire assessment program.

The plant configuration is different from the status of normal power operation and that of plant shutdown period. In this philosophy, the items that can be changed in their attributes of fire hazard and risk and reassessment is needed resulting from the configuration change. The following items show the above approach.

1) Changeable items at fundamental characteristics of combustible
   - quantity, position and location, and relative arrangement of fixed combustible
   - quantity of transient combustible and target
   - heat release rate and heat content of combustible at each fire area or compartment
   - characteristics of combustion zone followed by the variation of fire duration
   - time and temperature curve reflecting the flash-over, peak heat release rate, etc
   - variation of mass combustion rate, combustion product with elapse of time
   - major combustion parameters such as heat loss factor, radiation fraction, flame diffusion distance, etc
   - location of combustible inside fire area, such as wall, corner or center of the compartment
2) Alteration of fire area or fire zone
   - alteration of structure or geometry in single fire compartment
     - application of identical fire modeling with acceptable extension of fire area or zone
     - modification or change of fire modeling due to the sectional alteration
     - change of input data and relevant parameters with the application of the same fire modeling

- change from the single fire area or compartment to the multiple fire area or compartment
  - locational change from single area or compartment to multiple variation
  - change to multiple area or compartment in horizontal, vertical and complex structure
  - modification of analytical method due to the change of height, opening, and crevice

3) Alteration of fire resistance rating from the material change of fire barrier and the variation in their specification
- material change of fire barrier and partition
  - characteristic review and risk appraisal of the material in case of risk increase
  - change of structural form and performance effect from the intermediate partition, balcony and intrusion
- risk assessment items from specification change
  - internal temperature variation
  - characteristics of smoke diffusion in fire area or compartment
  - temperature distribution of combustion zone, ceiling jet area and hot gas zone

4) Type of ventilation and change of operation mode
- change in ventilation method
  - change in natural ventilation features due to the variation of opening, crack
  - change in ventilation features of the type #1, #2, and #3 force ventilation method due to the variation in suction and discharge opening
- change in ventilation features
  - change in the amount of infiltration and exfiltration
  - division between upper and lower layer and variation in opening area
  - fluid flow characteristic from horizontal and vertical ventilation opening and their mixture flow
- Fluid dynamics characteristic of smoke layer
  - temperature distribution of smoke layer
  - maximum increasing temperature of combustion layer and ceiling jet region

5) Variation of function and capability of the fire protection facilities
- change in actuation function of thermal detector
  - ceiling jet temperature and thermal layer movement due to change of fire protection area or compartment
  - possibility of functional failure or dysfunctioning due to change of thermal distribution
  - unfavorable effect to the thermal detector capability analysis program
- change in actuation function of smoke detector
  - malfunction or loss of detection capability due to the change of combustion gas flow
  - capability analysis based on characteristics and circumstances of thermal detector
  - modification of fire analysis modeling
- Capability change in fire suppression system
  - effective fire suppression capability and corresponding suppression area
  - loss of fire suppression capability to the adjacent combustibles

6) Other review items
- Type of critical fire and time-dependent variation of fire
- Critical damage temperature and heat flux to cable and circuits due to structure change
- Position and location of the combustibles
- Wind, Buoyant and Stack effect
- Fire bridage's fire fighting and capability for smoke control

3.2. Applicable Fire Modeling for the Fire Hazard and Risk Analysis

In general, fire hazard or risk evaluation is performed under the static condition without any configurational change during the power operation or low power operation modes. For this state, the applicable computerized program for zone modeling is, for example, FIVE[6], MAGIC, COMPBRN-Ⅲe. In addition, CFAST[7] is recommended as an effective performance-based fire modeling. The analyst should select these fire models under the specified fire scenario incorporated with fire compartment, combustible, ventilation condition, object and target, etc. In case of inappropriate condition or improper function at the time of program utilization, the program should be modified with a specific purpose or an additional calculative module should be provided for proper availability[8].

In case plant state moves from the operational mode to the shutdown, the analyst should evaluate the fire hazard and risk for the changed condition or transient situation. The purpose is to simulate the most proper fire modeling suitable to the fire scenario and target items what is required for analysis. The analysis result of the fire modeling will be reviewed and calculated by the analyst in detail and the final output will be confirmed by the expert with a specific evaluation.

In case of plant configuration change compared to that of normal operational state, or in case that there are some differences in analysis criteria for the fire risk and hazard analysis before and after the configuration change, the manual calculation will be used to find out the fire risk as well as the zone model approach by use of computerized program will be applied to find out the relevant analytical items from the configuration change as follows

1) Change in fundamental characteristics of combustibles
   - input result from manual calculation is required for the items of fundamental characteristics
   - modification of input parameters and time-dependent function after the review of primary computer output
2) Alteration of fire area or compartment
   - in case of single fire area of compartment
     - possible to apply CFAST, MAGIC, FIVE and COMPBRN-Ⅲe
     - parameters and conditions are different from input items at the time of power operation for fire hazard analysis
   - in case of multiple compartment or complex fire area
     - possible to analyze by use of CFAST, MAGIC, FIVE and COMPBRN-Ⅲe
     - in case of FIVE, manual calculation is needed to make equivalent evaluation for the multiple compartment
     - some modification of program is required in consideration of dynamic variation with time and the condition of the opening and crevice at the boundaries
3) Change in material and specification of fire barrier and partition wall
   - heat loss calculation through the fire barrier and partition
     - possible to check the wall temperature by use of CFAST, MAGIC, and COMPBRN-Ⅲe
     - for FIVE, the constant heat loss factor is applied consistently throughout the wall
   - evaluation of wall temperature from the specification change and heat loss features of the fire compartment
     - CFAST, MAGIC, and COMPBRN-Ⅲe are available to the thermal phenomenon analysis for the wall, floor and ceiling
     - except MAGIC, other models can not solve the multi-layer structure for the walls

4) Analysis for ventilation type and ventilation mode change
  - in case of mode change from the forced ventilation to the natural ventilation or the condition change of natural ventilation
    - opening analysis for each model is different, and it needs the expert review
    - analysis for the horizontal opening is possible by use of MAGIC or CFAST, but CFAST is available for a single opening
    - in case of natural ventilation, the analysis for the opening area change is only possible for MAGIC and CFAST
  - in case of forced ventilation or the condition change
    - CFAST, MAGIC, FIVE and COMPBRN-Ⅲe can analyze all types of forced ventilation
    - except MAGIC, the time-dependent condition of forced ventilation can not be available
    - analysis for the fluid dynamic of smoke layer can be possible by alteration of input condition from the configuration change
5) Actuation features for heat and smoke detector and fire suppression facilities
  - actuation features of detector
    - by use of CFAST, MAGIC, FIVE, the conditional change for the configuration is possible to interpret
    - dynamic actuation features of smoke detector should be evaluated on the basis of thermal detector
    - smoke movement and thermal environment as a result of configuration change should be evaluated
  - characteristic of fire suppression behavior
    - only the hydraulic water system can be evaluated by use of CFAST
    - when CFAST is used, it is estimated that heat release rate is decreased in proportional and concurrently to the suppression of hydraulic water. For the confirmation of this assumption, it needs to check the suppression capability through on-site real test
6) Additional risk evaluation items
  - time-reliant combustion rate and internal oxygen concentration : manual calculation or appraisal model
  - damage temperature or critical heat flux for cable or electric circuit : specific data is required for each material
  - evaluation for the adjacent combustibles : evaluation modeling is constructed with additional manual calculation
  - heat release rate for the position of the combustible and the evaluation of combustion product : manual estimation or modeling
  - wind effect, buoyant effect and stack effect : manual estimation or modeling
  - other quantitative items : quantitative or specific models developed for individual purpose

4. Conclusions

Fire risk and hazard analysis at nuclear powr plant that is requested at the time of power operation as well as the plant construction stage is performed for each fire area or compartment on the basis of plant configuration for normal operation. Periodic fire safety assessment, surveillance for the fire protection systems, and update of fire protection program are implemented on the referenced condition of power operation. On the other hand, if the situation of the plant arrangement came to be changed, such conditions as on-line maintenance during power operation or scheduled outage period for refueling, the existing fire protection area or compartment will be changed and not only the amount of combustibles but also their position will be altered from the design approach. Consequently, it is estimated that the physical status and fundamental condition are changed altogether. In addition to those variation, there are some transient phenomena in ventilation behavior and at the movement pattern in the compartment air flow. Considering these kind of changeable situation and transient behavior, it is quite difficult with consistency to establish a standardized way of fire risk and hazard.

In technical point of view, the relevant items for fire risk and hazard for configuration change in nuclear power plants are proposed at this paper and the fire analysis program for the detail analysis by use of zone model was presented with suggestion of applicable areas. Fire hazard analysis on the platform of plant configuration change for the shutdown period is under investigation deliberately in America and technically advanced countries and it is estimated for the regulation action requested for this discipline in a near future. Domestically in our conuntry, it is with the utilization of risk insight, with intentional purpose to build up the technical foundation and increase the capability to deal with this kind of intuitive needs. It is promising research field of risk evaluation technology and it is assured that by application of the core technology it will upgrade the safety of the nuclear power plant, achieve more economic benefit and enhance performance capability concurrently.

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