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核电厂安全参数显示系统中的安全参数选择和验证

SELECTION AND VERIFICATION OF SAFETY PARAMETERS IN SAFETY PARAMETER DISPLAY SYSTEM FOR NUCLEAR POWER PLANTS

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摘　要

叙述了核电厂安全参数显示系统中的安全参数选择与论证的方法和结果。根据核电厂安全分析，将核电厂的全面安全分解成六个关键安全功能，并严格选择了能够反映各安全功能的完整程度及其变化原因的安全参数。从使用核电厂应急规程的角度，并用全范围核电厂模拟器的事故演习对安全参数选择进行了论证。

SELECTION AND VERIFICATION OF SAFETY PARAMETERS IN SAFETY PARAMETER DISPLAY SYSTEM FOR NUCLEAR POWER PLANTS

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ABSTRACT

The method and results for safety parameter selection and its verification in safety parameter display system of nuclear power plants are introduced. According to safety analysis, the overall safety is divided into six critical safety functions, and a certain amount of safety parameters which can represent the integrity degree of each function and the causes of change are strictly selected. The verification of safety parameter selection is carried out from the view of applying the plant emergency procedures and in the accident manoeuvres on a full scale nuclear power plant simulator.

Although the direct reason that resulted in the TMI accident was the wrong judgement and decision of the operators, the important reason which led the operators to make wrong judgement and decision was the defect in the integrated design of the control room. The miserable fact is that the multitudinous alarm and instrumentation system did not work as what the designers expected that the instrumentation system should help the operators make quick and correct judgements. On the contrary, the operators could not know what signal was important and what was not important in the ocean of information. They did not know what event occurred exactly and what they should do against this event. Finally they made wrong judgements and actions one after one and caused the disaster of core melting of the nuclear power plant.

The reason was found that too many instruments were used and their arrangement was improper. They were not applicable to the surveillance of the plant safety status. Operators could not find the true reason and the extent of accidents from the unsystematic information provided by the instruments when an accident occurred.

The United States Nuclear Regulation Commission put forward the concept of safety parameter display system (SPDS) after summarizing the lessons of TMI accident. The SPDS can supply a set of dynamic critical safety parameters that the plant safety status can be supervised entirely with concentrated and properly distributed graphics. The number of the safety parameters should be minimum as possible. This purpose is to overcome the disadvantages of the previous instrumentation system used to supervise the plant safety status and substitute it with a simple, concentrated system which is strong in logic and is suitable to monitor the plant safety status.

The concept of the SPDS put forward by US NRC is adopted by the world. Now, a SPDS simulation system is being developed in Beijing Nuclear Power Plant Simulation Training Center of Tsinghua University.

1 BASIC PRINCIPLE FOR THE SAFETY PARAMETER SELECTION

Obviously, whether or not a SPDS is successful depends firstly on the selection of safety parameters which will be displayed. This kind of selection should include the correct parameter types and appropriate parameter number.

The safety parameters are selected according to the following principles:

(1) All parameters selected must be related to the plant safety, this means that the change of a parameter may reflect the occurrence, development and end of a certain kind of accidents;

(2) The whole set of selected parameters should be able to reflect each kind of the plant operating condition including power operation, hot standby and cold shutdown;

(3) The selected parameters should help the operators understand the nuclear power plant safety status and safety extent;

(4) The selected parameters should help operators judge the original causes of the plant accidents;

(5) The selected parameters should help operators use the emergency operating procedures to process the important accidents.

The number of parameters should be compromised between the following aspects. First of all, the number of displayed parameters should be as adequate as possible in order to: reflect the plant safety status independently. Operators need not depend on or refer to other information systems; reflect all important accidents entirely. These include the infrequant accidents and limiting accidents; reflect the special problems under different operating conditions of a nuclear power plant, such as the different paths of the core heat removal between power operating and cold shutdown.

Under the guidance of above principles, the displayed parameters should be as less as possible in order that operators can judge easily the plant safety status from the change of a minimum parameter set and avoid the disadvantages of the multitudinously and improperly arranged instrument panel.

To solve the contradiction that the parameters should be less as possible and the safety extent concerned by the SPDS should be as deep and broad as possible, a hierarchical display structure is used. The display is divided into levels according to the principle that the total plant safety can be divided into several safety functions. The general safety and each safety function can use separately a set of parameters of limited number to present them simply and clearly. The operator can obtain the most important parameters of the plant general safety (about 10 parameters) and the integrity degree of each safety function in a main graph. If the operator want to know more detailed safety status, he can call second or third level of the safety display graphs.

2 PARAMETER SELECTION

The parameter selection is from the view of the safety analysis of the nuclear power plant.

2.1 Division of a Nuclear Power Plant Safety —— Six Critical Safety Functions

Two concepts are included in the plant safety:

(1) To guarantee the safe operating condition: The most important thing is to ensure that the nuclear fuel power density and the departure from nucleate boiling ratio (DNBR) will not exceed the limitations due to distoration of reactivity and deterioration of thermodynamic condition. To avoid above phenomena, the following guarantee should be provided:

Proper reactivity control in order to ensure reactor have enough and available shutdown margin that the reactor is in a reliable subcritical condition after reactor trip;

Adequate cooling of reactor core. Sufficient coolant inventory and coolant flow through the reactor core should be maintained to prevent cladding temperature of the nuclear fuel exceeding the limitation;

Successful removal of the core heat. The removal capacity of the core heat by secondary loop must be ensured during power operation and initial cooling stage after reactor trip and by the residual heat removal system during plant cold shutdown;

Enough coolant inventory. A certain pressurizer level should be maintained under a normal operating condition. It must ensure that the reactor core is flooded with coolant in order to avoid reactor core's melting due to high temperature of the nuclear fuel even when a loss of coolant accident occurrs.

(2) To prevent radioactivity from leaking out to environment. Once above conditions could not be ensured, the important thing is to prevent radioactivity from leaking out to environment when a serious accident occurrs. For this purpose, three safety barriers are set up in the nuclear power plant:

The integrity of the fuel cladding. It is ensured to prevent broken pieces of nuclear fuel and radioactive materials from being released into the coolant through the broken fuel cladding;

The integrity of the pressure boundary of the reactor coolant loop. It is ensured to prevent the coolant with radioactive materials from being released further into the containment;

The integrity of the containment. It is ensured that the radioactivity which has been released into the containment should not be released further through the last barrier to nearby environment of the nuclear power plant to avoid its injuring people.

Synthesizing above two aspects, because there is no difference between the condition which keeps the integrity of fuel cladding and the condition which ensures the reactor core cooling, one of the two conditions can be deleted. Finally total plant safety can be divided into six critical safety functions: activity control, reactor core cooling, core heat removal, coolant inventory, pressure boundary integrity and containment integrity.

2.2 The Safety Parameter Selection for Monitoring Each Safety Function

According to the causality of plant safety, the safety parameters can be divided into two classes: The indicating parameters which show integrity degree of a certain critical safety function, and the monitoring parameters which supervise the causes about loss of this critical safety function.

(1) Reactivity control

Indicating parameters (a) neutron flux: It should decrease from power range to intermediate and source range according to the requirement of the technical specification in result to ensure reactor reliable shutdown after reactor trip: (b) startup rate: The startup rate of intermediate and source range should not be greater than zero in order to avoid neutron flux rising again after reactor trip.

Monitoring parameters: (a) control rod positions; (b) boron concentration; (c) concentration of the fission products xenon and samarium; (d) coolant average temperature.

In addition, $\Delta K/K$, axial and radial distribution, shutdown margin obtained through further calculation would reflect the reactivity control more essentially.

(2) Reactor core cooling

Indicating parameters (a) core exit temperature: It should be less than a certain value to prevent the nuclear fuel power density from over high; (b) coolant subcooling: It should be higher than a certain value to avoid the DNBR exceed its limitation.

Monitoring parameters (a) coolant cold leg temperature; (b) coolant average temperature; (c) coolant differential temperature; (d) total coolant flow through core (operating status of the reactor coolant pumps); (e) pressurizer level; (f) reactor vessel level.

(3) Core heat removal

Indicating parameters (a) steam generator (S/G) level; (b) main and auxiliary feedwater flow; (c) residual heat removal (RHR) pump discharge flow.

The proper S/G level, feedwater flow and its water resource should be provided during initial stage of reactor trip and RHR flow should be kept during plant shutdown.

Monitoring parameters (a) S/G Pressure; (b) condenser vacuum; (c) condensate storage tank level; (d) feedwater temperature; (e) RHR pump discharge temperature.

(4) Coolant inventory

Indicating parameters (a) pressurizer level; (b) reactor vessel level.

The full level of the reactor vessel and a certain level of pressurizer should be kept during normal operation. It should be paid attention to the false rise of the pressurizer level and development of the steam void in the reactor vessel when a small break of coolant loop occurrs.

Monitoring parameters (a) charge flow; (b) letdown flow; (c) reactor coolant pump seal return flow; (d) chemical volume control tank level; (e) pressurizer relief tank level; (f) containment sump level.

(5) Primary loop pressure boundary integrity

Indicating parameters coolant pressure. The abnormal decreasing of the reactor coolant pressure often shows the loss of primary loop integrity.

Monitoring parameters (a) coolant cooldown rate; (b) coolant cold leg temperature; (c) containment radioactivity; (d) pressurizer relief tank level; (e) secondary loop condenser and S/G blowdown radioactivity.

(6) Containment integrity

Indicating parameters containment pressure. It should be less than the design limitation of containment pressure.

Monitoring parameters (a) containment temperature; (b) containment radioactivity; (c) containment hydrogen concentration; (d) containment isolation status.

According to the principle of hierarchical display, a small group of parameters which can reflect the integrity degree of each critical safety function in highest sensitivity are selected from above indicating parameters as a set of the general safety indicating parameters of a nuclear power plant.

After systematic analysis and comparison, the following eight parameters or their alternative parameters are determined: (a) nuclear power / neutron flux (when nuclear power is less than 5%); (b) pressurizer level / reactor vessel level (when pressurizer level drops below to zero); (c) coolant average temperature / reactor exit temperature (when forcing coolant recirculation is lost); (d) S/G level / RHR pump discharge flow (when reactor is at cold shutdown); (e) coolant pressure; (f) containment pressure; (g) containment radioactivity / secondary radioactivity; (h) coolant subcooling.

3 VERIFICATION OF THE SELECTED SAFETY PARAMETERS

The verification is from the view of using emergency operating procedure. The emergency operating procedure is a set of procedures with which operators can handle various emergency accidents occurring at any plant operation time. All parameters in the emergency procedure used by operators to judge accident nature and to monitor accident development are related closely to the plant safety. In addition, one of the important purposes to design a SPDS is to help operators take actions to eliminate or mitigate accident consequence with emergency procedures. So, the most important parameters involved in the emergency procedures can be applied to verify the correctness of the safety parameter selection in the SPDS.

After the analysis of the emergency procedure formulated by Westinghouse Corporation the following conclusion can be drawn:

The number of the main independent parameters involved in End Path Procedure, which is used to handle urgently the design basis accidents, such as LOCA, MSLB, SGTR and station blackout, altogether are 12 (not including the bistable status of plant systems). They are core exit temperature, cooldown rate(*), coolant pressure, coolant subcooling, cooldown limitation of coolant temperature and pressure(*), pressurizer level, reactor vessel level, S/G level, S/G pressure, S/G feedwater flow and neutron flux(that noted with (*) is a dependent parameter). All of them have been included in the list of selected safety parameters.

The number of the main independent parameters involved in Critical Safety Function Status Trees and Function Restoration Procedure, which is used to judge critical safety function and to choose a proper restoration procedure and actions, amount to 14(not including the bistable status of plant systems). They are nuclear power, startup rate (intermediate and source range), core exit temperature, coolant subcooling, reactor vessel level, S/G level, S/G pressure, S/G feedwater flow, coolant cooldown rate(*), coolant cold leg temperature, coolant pressure, containment pressure, containment radioactivity, containment sump level and pressurizer level (that noted with (*) is a dependent parameter). All of them have been included in the list of the selected safety parameters.

It is thus obvious that the scope of the selected safety parameters is basically identical to the scope of the main parameters concerned in the emergency procedures.

4 CHECK OF THE SELECTED SAFETY PARAMETERS

The accident manoeuvre on a full scale PWR simulator is used to check the selected safety parameters. The nuclear power plant training simulator can simulate correctly various accidents occurring possibly inreal nuclear power plant, so the simulator can be used to check the rationality and exactitude of the safety display parameter selection. It is checked if each accident can be reflected with more than one selected safety parameters which change is significant to find and distinguish an accident from others. Above capabilities of each selected parameter were recorded and estimated during whole testing course.

Therefore, all selected safety parameters can be divided into four classes according to their sensitivity and correctness to reflect a kind of accidents.

First, exact and sensitive parameters. This kind of parameters not only can reflect sensibly an accident occurrence, but also can differentiate easily one accident from others.

Second, sub-sensitive parameters. When a kind of accidents occurr, these parameters might change, but the scope of their change in amplitude or in time is not significant to verify exactly an accident occurrence.

Third, inexact parameters. Their change can lead operators' misunderstanding of an accident occurrence, because the responses of this kind of parameters might be quite different during a same kind of accident.

Last, insensitive parameters. They do not change basically following an accident occurrence or their change are not related to the occurring accident.

For a SPDS, we should select the exact and sensitive parameters, do not select insensitive parameters (unusable), must not select the ambiguous and inexact parameters (confusable). Nevertheless, what class each parameter belongs to is changeable quite a lot for different accidents. At an accident a parameter may be inexact or insensitive, but at another accident it may be a exact and sensitive parameter. Therefore, we must select the most suitable indicating parameters against to each different accident.

We used the PWR nuclear power plant training simulator which has been operated in Beijing Nuclear Power Plant Simulation Training Center of Tsinghua University to check all the selected safety parameters.

While choosing simulated accident types for parameters check, we considered that the various accidents related to the general safety and all of the critical safety functions, accidents with different failure mechanism and special problems in different operating conditions. Some multipled accidents were considered too.

The result of tests is shown as the following:

(1) The most of accidents have more than one exact and sensitive parameters and some sub-sensitive parameters to reflect their status. With the aid of these parameters changing trend, operator can easily find accident occurrence, its nature and seriousness extent. It is obvious that the capability of selected safety parameters set to reflect the plant safety status is adequate.

(2) The most of selected parameters can exactly and sensibly reflect a kind of critical safety function or a kind of plant accident. It is obvious that the selected parameters set is representative and effective, too.

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