APPLICATION OF A SHUTDOWN SAFETY FUNCTION MONITORING SYSTEM

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1. INTRODUCTION

The Maanshan Nuclear Power Station shutdown safety function monitoring system (SDSMS) is a user-friendly computer code, which can be set up on a personal computer. During shutdown operations this program is able to request data from the plant computer to perform on-line safety parameter monitoring and safety function performance trending functions. The key safety functions (KSF) which were well defined in NUMAC 91-06 include core reactivity (CR), decay heat removal (DHR), reactor cooling system (RCS) inventory, reactor integrity (RI) and containment integrity (CI).

In these few years, the licensee has used the NUMAC 91-06 guidelines and plant specific procedures to establish the plant's shutdown safety policy. Even under this restricted administration control it still cannot be assured that an accident will not happen. An incident's cause might come from a degradation of the safety system's performance, a bad temporary seal or cap installation (??). The SDSMS plays an independent role, to supervise plant safety during a shutdown condition. From the display of safety indicators an operator will readily know the plant's safety status and the margin of risk. Furthermore, the SDSMS history function will help the user to determine an incident's root cause. Especially, during the mid-loop operation, the SDSMS will watch the overall KSF variations, like RCS inventory and decay heat removal from all available computer point signals. In our shutdown operation experiences, the SDSMS has already successfully prevented some unexpected situations from getting worse, including the inventory loss of RWST during SI pipe refilling, inadvertent dilution of RCS during plant heat-up and non-safe inventory control during mid-loop operation. After the application of the SDSMS in the last refueling outage, we found it reduced both plant risk and incident occurrence during the shutdown operation.

2. KEY SAFETY FUNCTIONS IN THE SDSMS

The SDSMS monitored KSF which were well-defined in report NUMAC 91-06. The SDSMS was designed to watch for KSF degradation to avoid KSF loss prevention. Six KSF are monitored in the SDSMS model:

1. Reactivity
2. Decay-heat removal
3. Reactor cooling system inventory
4. Reactor integrity
5. Containment integrity
6. Electric power supply availability

2.1 Reactivity

During shutdown operation adequate core shutdown margin is needed, especially during a plant overhaul outage. When the plant is at cold shutdown, all control rods are fully inserted into the core and the operators do not have the ability for immediate negative reactivity insertion. So reactivity control is the most significant KSF in this time window. It is very easy to understand why we must stop the reactivity increasing at the beginning of any inadvertent reactivity insertion.

The SDSMS reactivity monitoring function was based on the trending of the ex-core source range (SR) detector's readings since changing of core reactivity will affect the ex-core detector readings. The SDSMS will calculate reactivity changes according to the CPS variations and show the results on the reactivity risk meter. Figure 1 displays the generic concept of the SDSMS reactivity monitoring function.

The reactivity variation formula was derived from the sub-critical multiplication theory. When the core is in a sub-critical condition with fuel and neutron source, a positive reactivity insertion will increase the neutron generation rate, as follows:

$$S = S_0 \, (1 + K_{eff} + K_{eff}^{2} + K_{eff}^{3} + K_{eff}^{4} + *)$$

$$S = S_0 \frac{1}{1 - K_{eff}}$$

where:

S is the SR reading after reactivity changed

S_0 is the SR initial reading before reactivity changed

K_{eff} is the effective multiplication factor

When core reactivity changed from status 1 to 2, we can use the following formula:

$$\frac{C_1}{C_2} = \frac{1 - K_{eff-2}}{1 - K_{eff-1}}$$

where:

C_1, C_2 are the SR readings (CPS) at status 1 and 2 respectively,

K_{eff-1}, K_{eff-2} are the effective multiplication factors at status 1 and 2 respectively

$$\Delta\rho \approx \ln \frac{K_{eff-2}}{K_{eff-1}}$$

Then the reactivity changes:

$$\Delta\rho \approx \ln\left[\frac{1}{K_{eff-1}} - \frac{C_1}{C_2} * \frac{1 - K_{eff-1}}{K_{eff-1}}\right] * 10^5 \text{pcm}$$

If $\Delta\rho > 0$ and the value is higher than the set point. the reactivity KSF meter will turn to a red color and show the amount of $\Delta\rho$ value.

2.2 Decay-heat Removal (DHR)

After reactor shutdown, the reactor thermal power will rapidly decrease to a small value dominated by decay heat. This situation will be sustained for a long time period until spent fuel is discharged. When the reactor cooling system (RCS) temperature and pressure are higher than 350℃ and 425 psig (in mode 3) the plant will use the steam generator (SG) to remove decay heat. When the RCS temperature and pressure are lower (below mode 4) the operator will assign the residual heat removal (RHR) system for shutdown cooling operation. The SDSMS will use the RHR inlet/outlet temperature and flow rate to calculate the amount of DHR and compare with the core decay heat. The formulae are as follows:

$$Q_{RHR} = m\, C_P\, (T_{out} - T_{in})$$

$$Q_{DH} = Q_0 * 0.095 * t^{-0.26}$$

where:

Q_{RHR} is the decay heat removal by the RHR system

Q_{DH} is the reactor decay heat generation

Q_0 is the reactor thermal power before shut down

m is the RHR system flow rate

C_P is the specific heat capacity

t is the time after reactor shutdown in seconds

When the RCS is in cool down operation Q_{RHR} should be larger than Q_{DH}. Otherwise the DHR KSF risk meter will turn to the color red and induce an alarm message.

2.3 RCS Inventory

There were different RCS operation levels for each stage of the shutdown operation. It was very difficult to determine the operation level setting for the SDSMS RCS inventory monitoring function. So monitoring the rate of change in the RCS level was considered to be the major part in this function. The SDSMS uses a least square fitting to estimate the level change rate. When the level decrease rate is higher than the limit, the RCS inventory KSF risk meter will turn to the color red.

When the operators follow the outage schedule to decrease the RCS level (for example reduced inventory to mid-loop operation) they may choose the inventory control option to predict when they will arrive at the target level. Each time when data are renewed, the system code will calculate the level change rate and update the completion time. This option is very useful, especially during the transition to mid-loop operation. The operators do not have to always worry about the completion time. This option gives the operators more confidence in their activities. The generic concept is shown in Figure-3.

2.4 RCS Integrity

The SDSMS considered two ways to take care of the RCS integrity. One was for low temperature over pressure (LTOP) prevention and the other was for reactor heat up/cool down operation. In this function the SDSMS reads in the RCS temperature and pressure to estimate the margin to pressure limit. The pressure limits come from a PZR PORV actuation curve and reactor heatup/cooldown curve, which were defined in the technical specifications (TS). Another concern was that the reactor heatup/cooldown rate should not be higher than 50C/hour. The RCS integrity KSF risk meter will show the results. If the margin is less than the default setting the SDSMS will alert the operator to pay attention to the KSF.

2.5 Containment Integrity

The plant’s TS regarding containment and fuel building integrity must be adhered to during refueling operations. This function was included in the SDSMS and the KSF risk meter will show the margin to the TS’s limit.

2.6 *Defense-in-depth*

Defense-in-depth was an important concern in the SDSMS. Consideration of defence-in-depth enhanced the SDSMS 's reliability and let it really act on a functional basis. For example, the decay heat removal in the SDSMS not only monitored decay heat removal by the RHR system but also the heat delivered by the component cooling water (CCW) system and nuclear service cooling water (NSCW) system. Additionally, SDSMS monitored the supporting system operation, like the electric power supply system, to complete the defense-in-depth concept.

3. CASE STUDY

In the past few years, the Maanshan Nuclear Power Station (MNPS) has applied the SDSMS to strengthen the plant's shutdown safety policy. We found it was very useful; enhancing not only the ability to trace back an event's root-cause but also for the prevention of KSF losses. Following is a typical case that happened during an MNPS unit 1 refueling outage. In this case the SDSMS played as a backup tool (because SDSMS was still in test) to help the operator successfully determine the problem.

When most unit 1 outage activities were completed and we were prepared to enter refueling mode, the operators followed the schedule to line up the SI system piping for filling and venting. When the operators opened the RWST outlet isolation valve and started to fill the low head SI piping, they saw the inventory had decreased and the auxiliary building sump level had increased. Field operators soon found that there was a heat exchanger seal leaking and immediately stopped the leakage. Operators then changed shift and continued to fill the high head SI system. After two hours of filling, the operators thought the SI system filling should be completed; but they saw that the RWST level was still slowly decreasing. The RO passed the information to the shift SRO and asked the field operators to check the high head SI piping room. The field operators checked each room repeatedly but nothing was found. The schedule was held to avoid further inventory loss. Finally the shift supervisor directed the operators to close the RWST isolation valve and organized a team of day shift operators to identify the problem. The office SDSMS user observed this situation from the SDSMS display and contacted the control room safety SRO. From the SDSMS history trending function, it was very easy to see that the RWST level was still slowly decreasing before the operators had started to fill the low head SI system piping. After a short discussion the safety SRO agreed that the problem had existed at the beginning of the SI system filling. It was very easy to find the inventory lost from BK (Containment spray) system. A venting plug had been removed for ILRT test. This abnormal condition was restored and the outage schedule was continued.

Actually there have been other cases that might probably challenge the KSF. For example, inadvertent dilution of the RCS caused by mixing bed replacement, and inventory lost during system pipe filling has occurred frequently. We found the SDSMS played an important role that was independent of the plant's administrative control.

4. SUMMARY

The scope of activities during a normal refueling outage is large and diverse. In the Maanshan NPS we used plant-specific shutdown safety operation procedures and NUMAC 91-06 guidelines to establish our shutdown safety policy. But we found those key safety functions (KSF) were not easy to figure out. Besides, it was very difficult for operators to know how close the plant was to risk. That's the reason why we developed the shutdown safety function monitoring system. With the SDSMS we can give operators an indication about the KSF risk margin.

After we set up the SDSMS, whenever the KSF was degraded, the SDSMS would immediately display an appropriate alarm message. So the operators will have more margin to handle the abnormal situation. We found the SDSMS played an important role that was independent from the plant's administrative control, and it really strengthened our plant's shutdown safety.

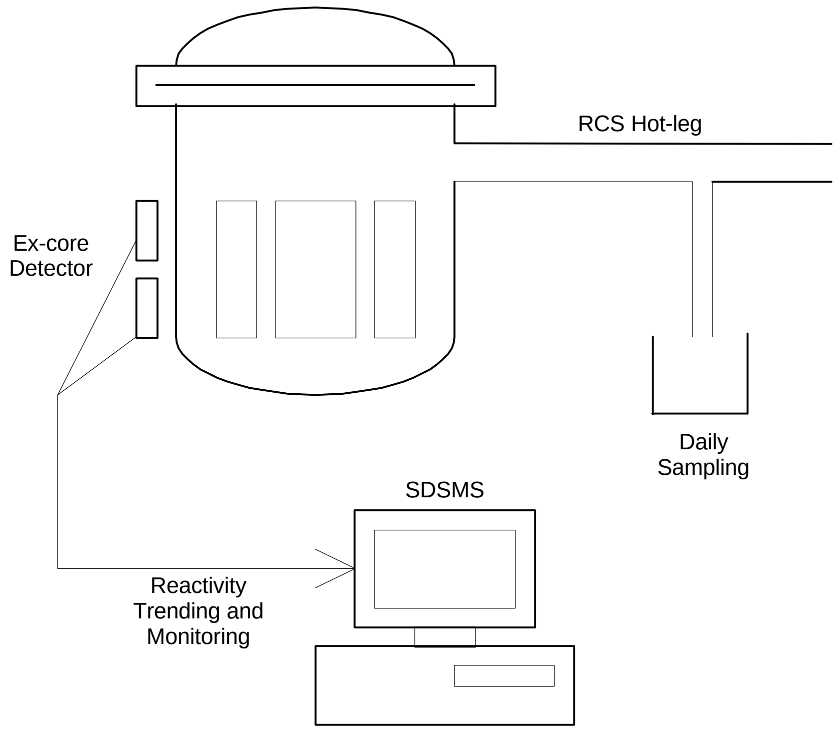

Figure 1. SDSMS Reactivity Key Safety Function Design Concept

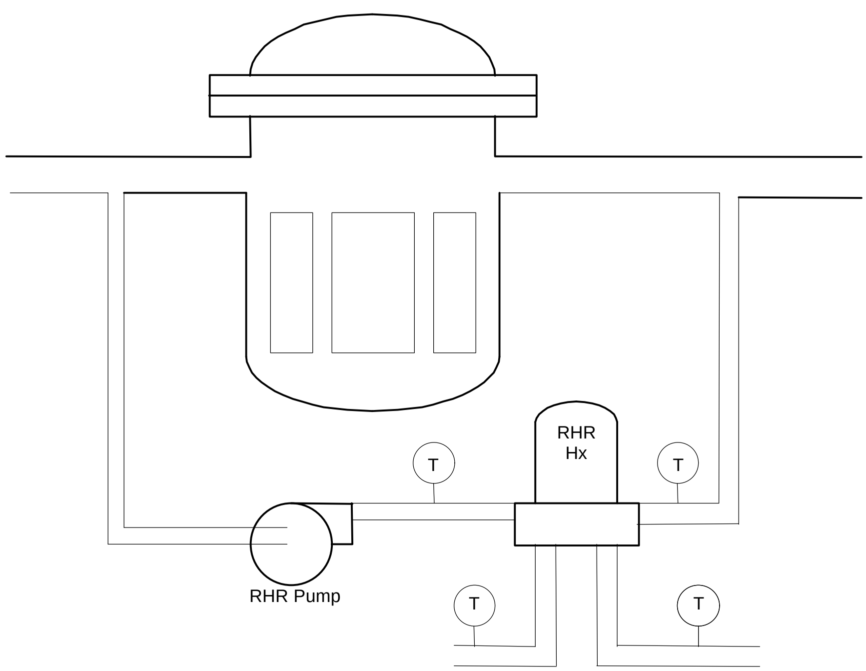

Figure 2. SDSMS Decay Heat Removal KSF Calculation Concept

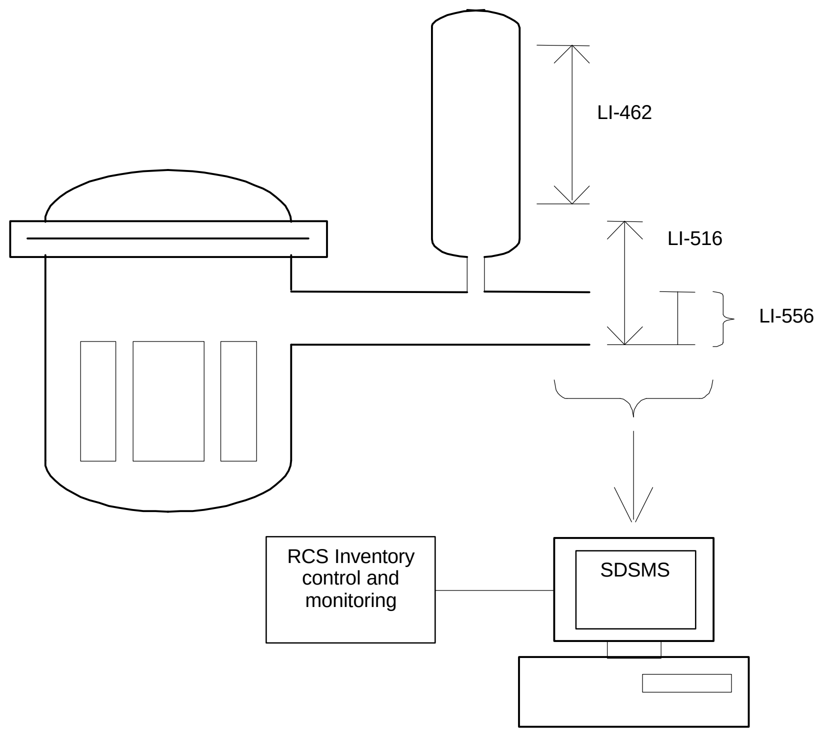

Figure 3. RCS Inventory Key Safety Function Design Concept

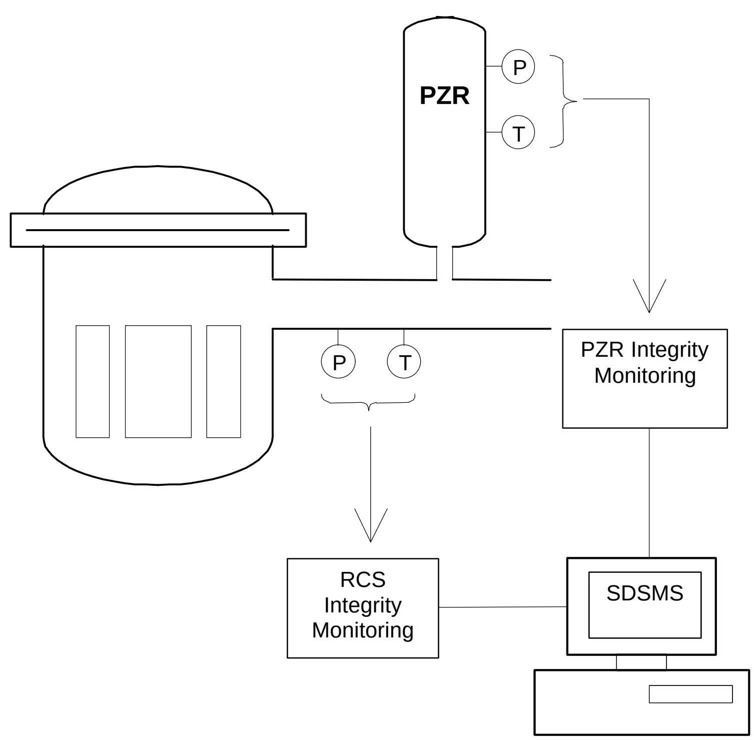

Figure 4. RCS Integrity Key Safety Function Design Concept

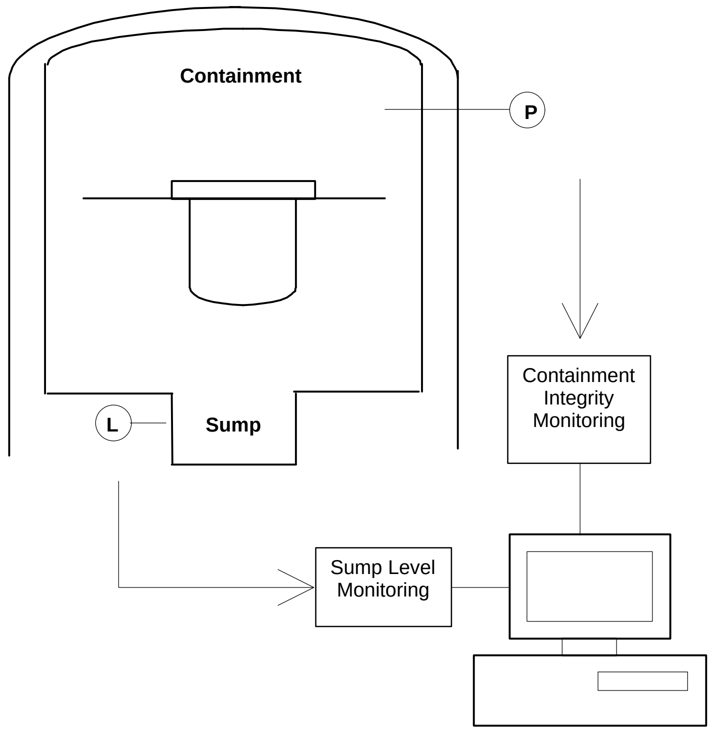

Figure 5. SDSMS Containment Integrity KSF Design Concept