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Design Improvement for the Cooling System of the Interim Spent Fuel Storage Facility Using a PSA Method

Won Il Ko, Jong Won Choi, Seong Won Park, Jae sol Lee, and Hyun Soo Park
Korea Atomic Energy Research Institute
150 Dukjin-dong, Yusong-gu, Taejon 305-353, Korea

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Abstract

With emphasis on safety, this study addresses for better design condition for the cooling system in a wet-type interim spent fuel storage facility, using a probabilistic safety assessment method. To incorporate the design renovation into the design phase, a simple approach is proposed. By taking the cooling system of a reference design, a fault tree analysis was performed to identify the weak point of the considered system, and then basic factors for design renovation were defined. A total of 21 design alternatives were selected through the combination of the basic factors. Finally, the optimum design alternative for the cooling system is derived by means of the cost and effect analysis based on the estimated cost, system reliability and assumed probabilistic safety criteria.

With the assumption that the failure frequency of at-reactor spent fuel cooling system compiles with probabilistic safety criteria for the interim spent fuel cooling system, it was shown that the optimum alternative should have 100% cooling loop redundancy with one pump per cooling loop and a cleanup system installed separately from the main loop. Furthermore, it also should be classified into safety system.

The result of this study can be used as a useful basis to identify factors of safety concern and to establish design requirements in the future. The method also can be applied for other nuclear facilities.

1. Introduction

The probabilistic safety assessment(PSA) method has been mainly applied to improving the safety of nuclear facilities since WASH-1400 report[1] in 1975. Recently, some analytical tools have been developed to obtain an optimum design condition[2,3]. Most of their applicable scopes, however, are limited to reliability optimization with only redundancy or/and a cost as a constraint. It is very difficult to apply these kinds of analytical tools to nuclear facilities that have lots of complicated subsystem and many constraints such as safety grade, probabilistic safety criteria, redundancy and cost.

This study was conducted to develop a simple approach method for design renovation of nuclear facilities and then to establish better design conditions for the cooling system of Interim Spent Fuel Storage Facility designed conceptually in Korea.

An approach of cost and effect analysis linked with probabilistic safety criteria was proposed to incorporate the optimum condition in the design phase. The alternative with minimal cost, within the safety requirements on the cost versus reliability plot, was assumed to be an optimal design. It means that the purpose of the optimum design of facility is not to increase its safety but to minimize its construction cost from the view point of engineering sense. Figure 1 shows the procedure to obtain the optimum design alternative proposed in this study. By taking the cooling system of a reference design, the study began with a fault tree analysis to identify the weak point of the system, and then basic factors for design renovation were defined. Reasonable design alternatives were selected through the combination of the basic factors, and then construction costs were estimated for each alternative. Finally, the optimum design alternative for cooling system is selected by performing the cost and effect analysis linked with assumed probabilistic safety criteria.

2. Reference Design

For this study, the conceptual design performed by KAERI(Korea Atomic Energy Research Institute) in 1990[4] is taken as a reference system, as shown in Figure 2. The cooling system consists of three normal loops and of an emergency pool water makeup. The main function of the pool cooling system is to maintain the storage pool water temperature below appropriate temperature limits by removing decay heat generated from spent fuel. Heat is extracted from the storage pool to the secondary cooling loop through the heat exchanger, and then to the sea water cooling loops. All of the cooling systems consist of three identical cooling loops and each loop has 50 percent capacity of decay heat removal and 100 percent pump redundancy in parallel (one in operation and the other in stand-by). The pool cooling system shown in Figure 3 is also provided with cleanup system which removes impurities from the spent fuel storage pool water to ensure optical clarity and to limit the concentration of radioactivity in the water. A part of pool water flow on each loop is purified continuously through the filter and the mixed bed of the cleanup system before cooling.

In the conceptual design, all cooling systems including emergency pool water makeup system were defined as safety class 3 and pool cleanup systems as non-nuclear safety class. This matter on safety grade has been an argue point in the conceptual design phase because there is no any requirements on safety grade for the cooling system of independent spent fuel storage facility.

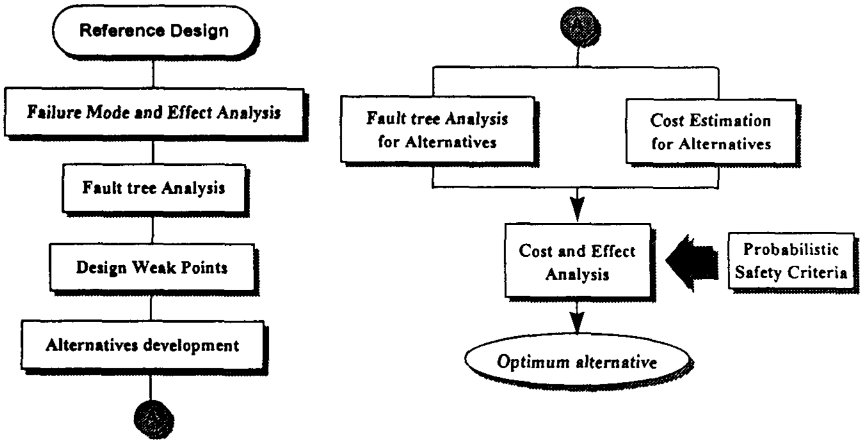

Fig. 1. Calculation Procedure to Obtain the Optimun Alternative

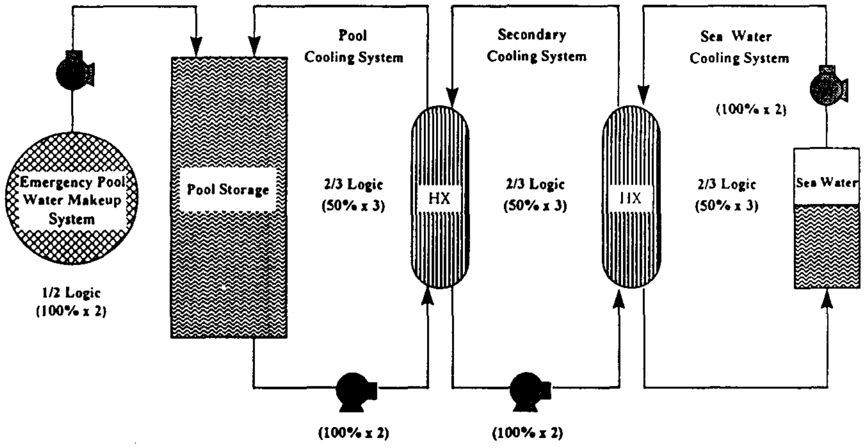

Fig. 2. Flow Diagram for the Cooling System of Reference ISFSF

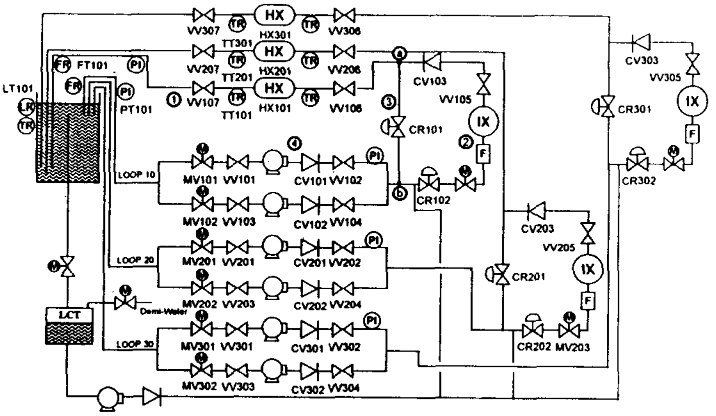

Fig. 3. P&ID of the Pool Cooling System in Reference ISFSF

3. Fault Tree Analysis

3.1. Applicable Codes and Failure Data

To perform fault tree analysis, SRA(System Reliability Analysis) code package[5] was used. This package consisted of four codes of different functions-FTAP, FRANTIC, IMPORTANCE. The FTAP code is a general purpose computer program for fault tree analysis, and the FRANTIC code is to calculate the time dependent unavailability. The IMPORTANCE code is to compute various top event characteristics as well as measures of probabilistic importance of basic event and minimum cut sets of a fault tree.

Component failure data of this study were referred from the literatures because the reference design was only on conceptual design level. Accordingly, general failure data of nuclear power plant[6] which were prepared for IPE of YGN unit 3-4 were used for the components identified as safety grade. The failure data of THORP storage facility in the United Kingdom[7] for the component identified as non-safety grade were used because the facility was designed as non-safety grade with capacity of 3,000 MTU. The MTTR(Mean Time To Repair) in Reference 9 were used for some components and equipment.

3.2. Top Event Determination

Unlike the dry storage system, the pool system could experience a failure in the active cooling system which, if not repaired in time, could lead subsequent to fuel heat up, water heat up, boiling of pool water, and eventually fuel failure and activity release. In this study, the occurrence event of bulk boiling of pool water is taken as a top event assuming that bulk boiling of pool water can be a break point of loss of integrity of spent fuel. Although a cooling system could be failed, it was analysed to take several days to occur bulk boiling of pool water[8]. So the top event includes a conditional function that could not be restored in time.

The fault tree shown in Figure 4 illustrates the failure situation of the cooling system, that is, the top event can occur if all cooling systems fail and then the cooling system are not restored in time.

Generally, the frequency of the top event occurrence can be expressed with failure rate shown in Figure 4, as follows;

$$F = (R_1 + R_2 + R_3) \times RM \times RC \qquad (1)$$

Where,

R_1 ; failure rate of pool cooling system
R_2 ; failure rate of secondary cooling system
R_3 ; failure rate of sea water cooling system
RM ; failure probability of emergency pool water makeup system
RC ; conditional function

The R, R2 and R3 of eq. (1) are calculated from computer codes referred section III. 1 according to general fault tree analysis procedure, and the conditional function (RC) can be obtained with an analytical tool.

To calculate the conditional function, an exponential repair law was assumed as follows;

$$RC(T) = \mathrm{EXP}[\frac{-T}{\tau_s}] \qquad (2)$$

where T ; allowable time for restoration
τ_s ; mean time to repair

The mean time to repair, τ_s, in eq. (2) can be obtained by IMPORTANCE code which is assumed to be with constant failure rate and constant repair rate. The allowable time for restoration, T, which means the time to reach bulk boiling of pool water after failure of all cooling systems can be calculated

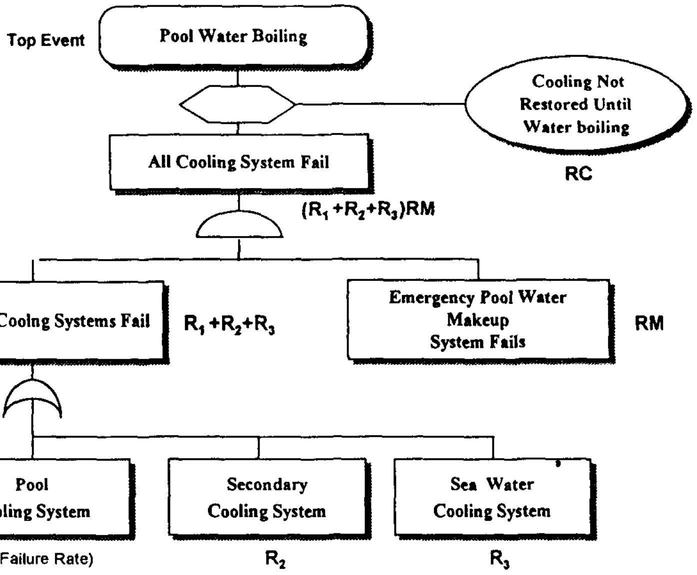

Fig. 4. Fault Tree Diagram for the Cooling System of Reference ISFSF

by an analytical method[8] as follows;

$$\triangle T = \frac{MC_p \triangle t}{Q} \quad (3)$$

where,

Q ; heat source rate(kcal/sec) = D-E

D ; decay heat produced in the pool(kcal/sec)

E ; evaporation heat loss(kcal/sec)

C_p ; specific heat of water(kcal/kg. ℃)

$\triangle t$; difference of pool water temperature(℃)

M ; pool water mass(kg)

By the eq. (3), the elapsed time that the pool water temperature reaches to 100℃, from normal temperature of 20℃, would be about 6.38 day.

4. Results and Discussion

4.1. Fault Tree Analysis for Reference Design

A failure mode and effect analysis(FMEA) was performed with an appropriate shut-down modes for the cooling system of reference design.

In case of high water flow difference between suction and return pipe or low level of pool water, a vent valve to avoid siphon phenomenon is automatically opened on the concerned treatment loop after alarm and warning in control room in sequence according to setting value, and recirculating pump is stopped and then a stand-by loop starts manually.

FMEA for main components of pool cooling system is shown in Table 1. The fault trees for the cooling systems of alternatives were also developed with the results of these FMEA. The pool cooling loop is divided into 2 nodes(ⓐ, ⓑ) and 4 segments(①~④) to facilitate fault tree development as shown in Fig. 2.

For fault tree analysis and its quantification, some assumptions to simplify fault tree networks are applied for the following items.

- The failure of level control system which compensate pool water evaporation are neglected to simplify the fault tree network. The failure of the system has not largely an effect on the cooling function of the pool water because the flow rate of this line ensures only 2% of that of the main loop.
- Emergency pool water makeup system(RM in eq. (1)) was not defined well and designed in conceptual design level. So an assumed value, 0.0025/demand, in reference (9) was used as the failure probability of the makeup system.
- The flow rate in cleanup system train (segment ② in Fig. 2) of the reference system is one third of flow rate of main train. The cleanup system train in case of loss of segment ③ is not sufficient to meet the cooling demand in operation. In case of the loss of the segment ②, activities of pool water will be increased and eventually exceeded the value of design requirement, 5×10^{-4} Ci/m^3 (8). So it is assumed that the loss of the segment ③ or the segment ② means the loss of concerned loop (loop 10).
- Human error and common mode failure as well as external events such as earthquake and missile are not also considered.

Although these assumptions have an effect on the absolute amount of reliability, the priority of alternative would not be nearly changed in view point of the relative performance comparison for alternatives as in this study.

Table 2 shows the result of probabilistic importance for basic event of the reference design. It can be seen from the result that the control valves are important elements for the top event. The control valves which indicate a weak point in the loop are used for controling the flow rate between main loop and clean up loop. It is indicated especially that the weakest point of the control valve is the standby control valve failure to open. It means that if the control valve is periodically checked more frequently the reliability of the system can be increased. In another point of view, it can be expected that if the cleanup system is installed separately from main loop, the control valves associated cleanup system are not

Table 1. FMEA for Major Equipment and Components of Pool Cooling System

equipment	failure modes	cause	effects on system	methods of detection	compensating provisions
heat exchangers (HX101,201, 301)	1. plugged	–corrosion –foreign object in system	–reduced flow in one system –gradual increase in temp in pool	–local temp. alarm(TR) –flow alarm(FR) in control room	–failed HX can be isolated by valve –redundant loop is provided.
	2. leakage	–causing crack –welding failure –manufacturing defects	–reduced heat removal –pool water level in system –gradual increase in temp. in pool.	–high pool temp. alarm (TR) –local temp. alarm(TR) –flow alarm(FR) –pool water level(LR) alarm	–failed HX can be isolated by valve –redundant loop is provided.
pumps (MP101,102, 201,202,301, 302)	1. fail to start	–electrical malfunction –mechanical failure –binding –loss of power	–failure of standby loop open. –fuel pool temp. will gradually increase.	–motor status in control room –local pressure indication(PI1)	–redundant loop is provided for continued flow for heat romoval.
	2. stops	–electrical malfunction –mechanical seizure –loss of power	–loss of flow –feul pool temp. will gradually increase.	–motor status in control room –high pool temp alarm (TR) –low pressure(PI) and flow alarm(FR) –local pressure indication(PI1)	–redundant pump train is provided for continued flow.
	3. fails deliver rated flow	–excess seal leakage –mechanical malfunction	–reduced flow –fuel pool temp. will gradually increase.	–low pressure(PI) and flow alarm(FR) –local pressure indication(PI1)	–redundant pump train is provided for continued flow.
	4. spurious startup	–electrical malfunction	none	–motor status in control room –local pressure indication(PI1)	–stop manually
control valves (CR101,102, 201,202,301, 302)	1. fails closed (normally open)	–electrical malfunction –mechanical failure	none	–local flow indication	–redundant loop is provided for maintenance
	2. fails to open(normally closed)	–electrical malfunction –mechanical failure –binding	–loss of flow (CR101,201,301) –fuel pool temp. will gradually increase. (CR101,201,301) –high pool activity (CR102,202,302)	–periodic check –high pool temp alarm (TR) –flow alarm(FR)	–redundant loop is provided for continued flow and activity control
	3. leakage	–mechnical failure(corrosion, causing crack, welding failure) –manufacturing defects	–reduced flow –fuel pool temp. will gradually increase.	–flow alarm(FR) –pool water level(LR) alarm	–redundant loop is provided for continued flow.
pool temp indicator (TR)	1. false low temp alarm	–set point drift –electrical malfunction –mechanical failure	–no direct impact on pool cooling –standby pump starts unintentionally	–local temp.(TR) –no coincident low temp gauge indication with low alarm –periodic check	–local temp indication needs when pump is running
	2. false high temp alarm	–set point drift –electrical malfunction –mechanical failure	–no direct inpact on pool cooling –standby pump starts unintentionally	–local temp.(TR) –no coincident low temp gauge indication with high alarm –periodic check	–local temp indication needs when pump is running

needed. Accordingly the total system can be simplified because one independent cleanup system is sufficient to meet purification criteria of the pool water, and the reliability of the system also can further be increased.

From the result of the system quantitative analysis by eq. (1) through (3), it appears that the allowable time for restoration(T) and the mean time to repair of the failed system(τ_s) are about 6.38 days and 11.8 hours, respectively. The conditional function(RC) obtained by eq. (2) indicates 2.32×10^{-6}. Failure rate of all cooling system($(R1+R2+R3)\times RM$ in eq. (1)) obtained from fault tree computer codes is 6.48×10^{-4}/year. Therefore, the probability of pool water boiling considered the conditional function and all cooling system failure indicates a value of 1.5×10^{-9}/year which is much less than that of the reactor core melting accident of nuclear power plant, which means that the total cooling system has sufficient reliability. In addition, it is indicated that the conditional function makes a great contribution to the probability of pool water boiling.

Table 2. Probabilistic Importance for the Basic Event of the Reference Cooling System

Rank	Fussell-Vesely		Barlow-Prochan	
	Basic event	Importance	Basic Event	Importance
1	CRO301	0.601	CRO302	0.295
2	CRO302	0.393	CRO302	0.193
3	CRF202	0.237	CRF202	0.116
4	PTO101	0.235	CRF102	0.115
5	CRF102	0.234	PTO101	0.109
6	CVL203	0.094	CVL203	0.046
7	MVO102	0.085	MVO102	0.042
8	MPR101	0.085	MPR101	0.025
9	FTH201	0.03	FTH201	0.015
10	TTO201	0.023	TTO201	0.012

CRO : Control valve fails to open.
CRF : Control valve fails to flow.
PTO : Pressure transsmiter fails to operate.
CVL : Check valve leakages
MVO : Motor operated valve fails to open.
MPR : Moter driven pump fails to run.

Basic factors for design renovation were defined from the weak point of the system as well as from the fact that the system is reliable enough. There are; the separation of cleanup system from main loop, pump redundancy, loop redundancy, and assignment of safety class. A total of 21 design alternatives could be selected through the combination of those basic factors, shown in Table 3.

4.2. Probabilistic Safety Assesment for Alternatives

Table 4 shows the probability to reach boiling point considered the conditional functions for alternatives. It is inferred that the failure rate of cases S7 and S10 installed separately from main loop are less than that of others. These results show similar trends in alternatives classified as non-safety grade. It is also

Table 3. Design Alternatives for the Cooling System of ISFSF

Alternatives	Loop Logic	Pump Redundancy	Separation of Clenup System	Safety Class
Case S1	1/1	X	X	O
Case S2	1/1	O	X	O
Case S3	1/1	O	O	O
Case S4	1/2	X	X	O
Case S5	1/2	X	O	O
Case S6	1/2	O	X	O
Case S7	1/2	O	O	O
Case S8	2/3	X	X	O
Case S9	2/3	X	O	O
Case S10	2/3	O	O	O
Case SB*	2/3	O	X	O
Case N1	1/1	X	X	X
Case N2	1/1	O	X	X
Case N3	1/1	O	O	X
Case N4	1/2	X	X	X
Case N5	1/2	X	O	X
Case N6	1/2	O	X	X
Case N7	1/2	O	O	X
Case N8	2/3	X	X	X
Case N9	2/3	X	O	X
Case N10	2/3	O	O	X
Case NB	2/3	O	X	X

indicated that alternatives classified as safety grade are much safer than those classified as non safety grade, that is, the assignment of safety class affects significantly on the reliability of total system.

Table 2. Probabilistic Importance for the Basic Event of the Reference Cooling System

case	frequency to reach boiling point	case	frequency to reach boiling point
S1	3.5×10^{-6}	N1	5.0×10^{-4}
S2	2.1×10^{-6}	N2	3.2×10^{-4}
S3	1.2×10^{-6}	N3	3.0×10^{-4}
S4	3.0×10^{-9}	N4	1.1×10^{-6}
S5	1.2×10^{-9}	N5	1.4×10^{-6}
S6	1.0×10^{-9}	N6	1.1×10^{-7}
S7	9.0×10^{-12}	N7	1.5×10^{-8}
S8	3.0×10^{-8}	N8	5.0×10^{-6}
S9	5.0×10^{-8}	N9	1.1×10^{-5}
S10	1.5×10^{-11}	N10	4.1×10^{-8}
SB	1.5×10^{-9}	NB	3.0×10^{-7}

Figure 5 shows the frequency to reach boiling point for alternatives and probabilistic safety criteria. Since there is no available probabilistic safety criteria for cooling system of the independent spent fuel storage facility, it is assumed to be $3.5\times10^{-8}\sim5.7\times10^{-9}$/reactor-year, the frequency to attain boiling point of pool water in spent fuel storage system at nuclear power plant(PSC-FS in the figure)[9]. It means that the cooling system of independent spent fuel storage shall be at least as safe as the cooling system of spent fuel storage in nuclear power plant. It is also compared with another value of PSC, $1\times10^{-4}\sim5\times10^{-5}$/reactor-year, which is reactor core damage frequency of nuclear power plant(PSC-CM in the figure). It indicates that most cases are below the PSC-CM, and the safest alternative is case S7 which has two loops with 100% pump redundancy, independent cleanup system, and identified safety class.

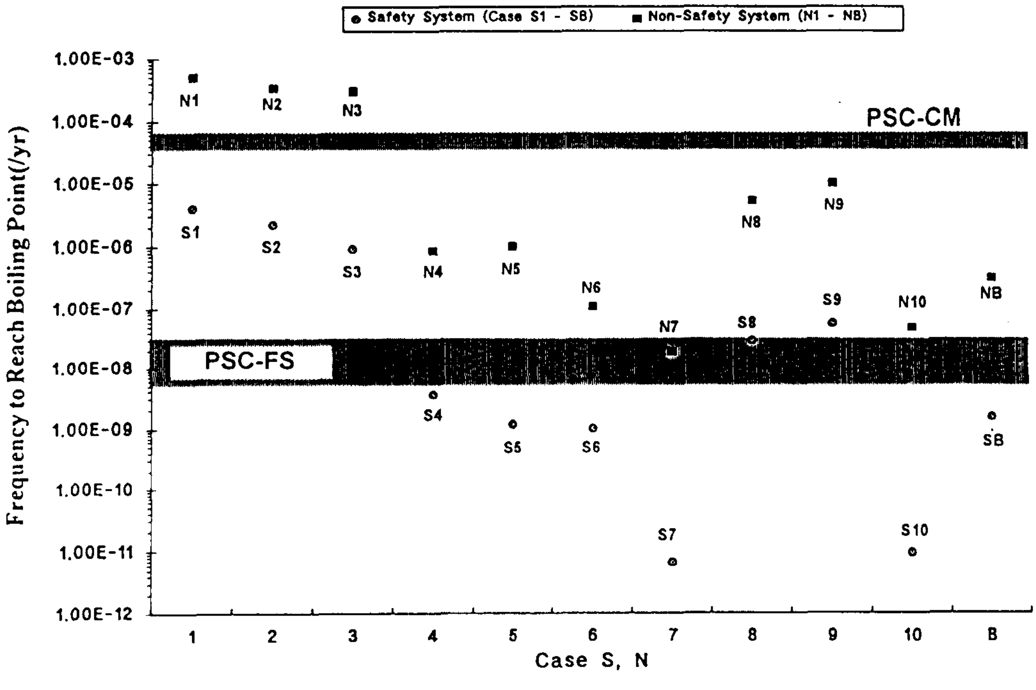

Fig. 5. Probability to Reach Boiling Point of the Storage Pool of ISFSF

Table 5. Capacities, Materials and Costs for Main Equipment and Component for Cooling System Configurations

system (logic)	equipment	materials[1]	capacities[2]	types	unit costs(10^3\$)[3]	
					safety grade	non-safety
storage pool cooling and cleanup system (1/1, 1/2)	heat exchanger	stainless steel	200m^2	plate	455	227
	pump	cast steel	730m^3/hr	centrifugal	238	79.4
	gate Valve	stainless steel	41.1cm	butter fly	31.05	10.4
	check Valve	stainless steel	〃	–	20.7	6.9
	motor Valve	stainless steel	〃	–	41.0	13.1
	regin precoated filter*	stainless steel	16.4m^3, 5μm	cartridge	–	300
	gate valve*	carbon steel	32.5cm	butter fly	–	5.52
	check valve*	carbon steel	〃	–	–	4.86
	motor valve*	carbon steel	〃	–	–	11.2
storage pool cooling and cleanup system (2/3)	heat exchanger	stainless steel	100m^2	plate	373	186
	pump	cast steel	365m^3/hr	centrifugal	197	65.5
	gate Valve	stainless steel	30.2cm	butter fly	21.7	7.24
	check Valve	stainless steel	〃	–	16.5	3.79
	motor Valve	stainless steel	〃	–	33.1	11.0
	regin precoated filter*	stainless steel	8.2m^3, 5μm	cartridge	–	238
	gate valve*	carbon steel	23.5cm	butter fly	–	4.48
	check valve*	carbon steel	〃	–	–	3.79
	motor valve*	carbon steel	〃	–	–	7.94
secondary cooling system (1/1, 1/2)	heat exchanger	stainless steel	614m^2	shell/tube	620	310
	pump	cast steel	730m^3/hr	centrifugal	238	79.4
	gate Valve	stainless steel	41.1cm	butter fly	31.05	10.4
	check Valve	stainless steel	〃	–	20.7	6.9
	motor Valve	stainless steel	〃	–	41.0	13.1
secondary cooling system (2/3)	heat exchanger	stainless steel	307m^2	shell/tube	480	240
	pump	cast steel	365m^3/hr	centrifugal	197	65.5
	gate Valve	stainless steel	30.2cm	butter fly	21.7	7.24
	check Valve	stainless steel	〃	–	16.5	3.79
	motor Valve	stainless steel	〃	–	33.1	11.0
sea water cooling system (1/1, 1/2)	filter	stainless steel	800m^3	mussel	100	100
	pump	cast steel	800m^3/hr	submerged	269	89.7
	gate Valve	stainless steel	50.5cm	butter fly	34.0	11.4
	check Valve	stainless steel	〃	–	24.8	6.9
	motor Valve	stainless steel	〃	–	46.2	15.4
sea water cooling system (2/3)	filter	stainless steel	400m^3	mussel	86	86.0
	pump	cast steel	400m^3	submerged	209	86.0
	gate Valve	stainless steel	31.4cm	butter fly	31.1	10.4
	check Valve	stainless steel	〃	–	20.7	6.9
	motor Valve	stainless steel	〃	–	36.0	12.0
cleanup system (separation loop)	regin precoated filter*	stainless steel	16.4m^3, 5μm	cartridge	–	300
	gate valve*	carbon steel	32.5cm	butter fly	–	5.52
	check valve*	carbon steel	〃	–	–	4.86
	motor valve*	carbon steel	〃	–	–	13.7
	pump	carbon steel	421m^3/hr	centrifugal	–	37.9

(1) safety grade case for main loop
(3) 1992 price pump : flow rate
* clean up system valve : diameter

(2) heat exchanger : heat transfer area
pump : flow rate
valve : diameter
filter : flow rate, pore size

4.3. Cost and Effect Analysis

The equipment and component's costs referred in the available literature[10] were used, in which provides cost data as a function of capacities or sizes and various non-nuclear graded materials for various components and equipment used in general chemical plants. So it is important to determine appropriated capacities and sizes of the equipment and components of cooling systems for all alternatives because the circulating flow rate required to dissipate decay heat load are different according to cooling system's logics. The calculation method and related input data used in this study are as follows;

- Circulation flow rate of cooling water

$$M=\frac{(C_p \triangle T)}{Q}$$

where, Cp ; specific heat
(4,187J/kg.℃ for pool water,
4,026J/kg.℃ for sea water)
$\triangle T$: cooling range(6℃)
Q : Heat source produced in the pool
(5.5MW, 3,000MTU of spent fuel)

This flow rate will be used to calculate pump capacities and sizes of pipes and valves for each alternatives.

- Heat transfer area of heat exchanger

$$M=\frac{Q}{(h \triangle T)}$$

where, h ; heat transfer coefficient of heat exchanger
(4,300kcal/m^2.hr.℃ for plate type,
1,400kcal/m^2.hr.℃ for shell and tube type)

- Optimum size of pipe[10]

$$D_{i,opt}=3.9 \times M^{0.45} \times D^{0.13}$$

where, h ; heat transfer coefficient of heat exchanger
(4,300kcal/m^2.hr. ℃ for plate type, 1,400 kcal/m^2.hr.℃ for shell and tube type)
(1,000 kg/m^3 for pool water,
1,024kg/m^3 for sea water)

The optimum size of pipe will be used to obtain pipe and valve sizes for each alternatives.

Table 5 show materials, capacities and sizes of the equipment and components of cooling systems as well as unit cost. An appropriate weighting factors (2~3 times) are assigned to the equipment classed as safety grade with engineering judgement. The engineering judgement is based on the fact that nuclear graded equipment has to be reflected the additional cost of material change(ex. from carbon steel to stainless steel) and quality control cost needed in the process of design and manufacture.

Figure 6 shows the construction cost of cooling system for alternatives classified as safety grade. It is indicated that the cost of cooling system with pump redundancy increase to about 37%~45% more than that with non-redundancy, and the cost of cooling system with safety grade increase to about 1.9~2.4 times more than that with non-safety grade. In case of a cleanup system installed separately from the main loop, however, the cost of alternative with 1/2 and 2/3 cooling logic decrease a little (see case 4 and 5, case 6 and 7) and the cost of alternative with 1/1 cooling logic increase a little (case 2 and 3). The reason is that, in case of a cleanup system installed separately from the main loop, only one loop of cleanup system is required regardless of cooling system logics.

Figure 7 shows the result of cost and effect analysis considering the construction cost and the probability to reach at boiling point of pool water for all the alternatives, as well as assumed PSCs. This figure shows that the reference design(Case SB) is the most expensive, but the reliability of the case SB is rather lower than those of case S7, S6, S10, etc. It means that the construction cost is not proportional to the reliability of a system. As shown in this figure, it is evaluated that the optimum alternative is Case S5 which indicates a minimum cost as well as meets

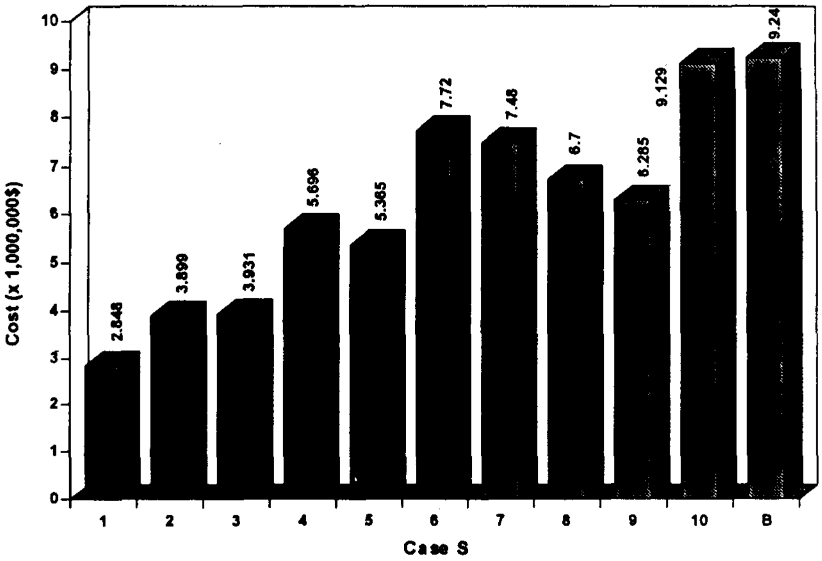

Fig. 6. Construction cost for coolong systems classified as safety grade

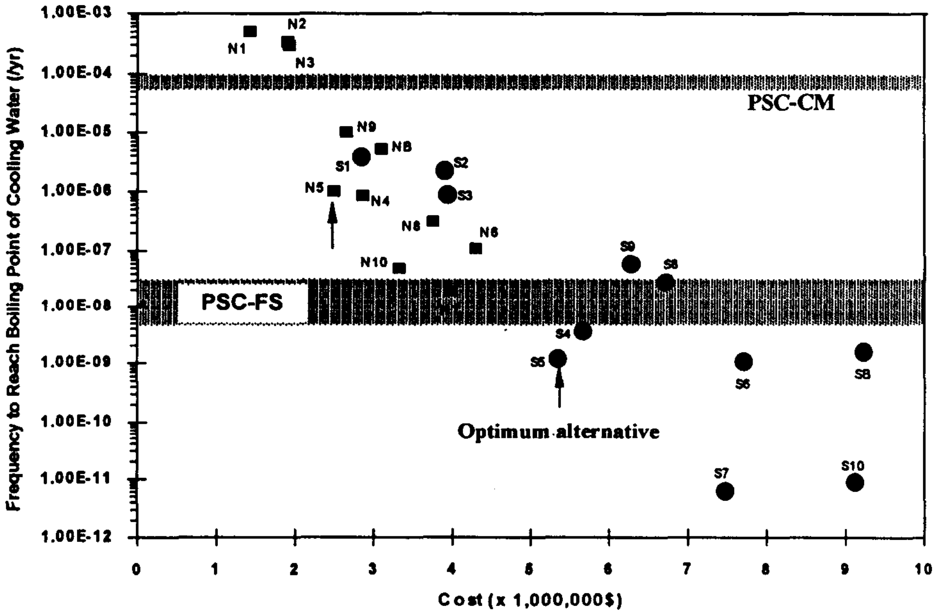

Fig. 7. Cost and Effect Analysis for Design Alternatives

assumed PSCs. The selected optimum alternative consists of 100% cooling loop redundancy with a pump per cooling loop and a cleanup system installed separately from the main loop. Futhermore, it should be also classified into safety system. Consequently, the cost of the cooling system for the optimized alternative could also be reduced to 60 percent of that of reference design.

5. Conclusions

The optimum design analysis by the approach proposed in this study could be concluded as follows:

- From the result of PSA analysis, the weak points in the loop appeared to be the control valves which would be used for controling the flow rate between main loop and clean-up loop.
- From the results of PSA and cost analysis, the endowment of safety class out of the basic factors was seen to affect significantly on the reliability as well as the construction cost of the cooling system.
- From the cost and effect analysis, it was shown that the optimum alternative was to consist of two cooling loops (100% redundancy) with a pump per cooling loop and a cleanup system installed separately from the main loop. Futhermore, it would be desirable that this system would be classified into safety class.

The results of this study could be used as basis for development of design requirements and for establishment of the safety concept. First of all, it is important to set up an appropriate PSC. The approach adopted in this study, if an appropriate PSC would be defined, could be useful for application to other nuclear related facilities.

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