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시스템즈 엔지니어링 기법을 이용한 격납용기 살수펌프의 신뢰기반 정비기법 도입 연구

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Systems Engineering approach to Reliability Centered Maintenance of Containment Spray Pump

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Abstract : This paper introduces a systems engineering approach to reliability centered maintenance to address some of the weaknesses. Reliability centered maintenance is a systematic, disciplined process that produces an efficient equipment management strategy to reduce the probability of failure [1]. The study identifies the need for RCM, requirements analysis, design for RCM implementation. Value modeling is used to evaluate the value measures of RCM. The system boundary for the study has been selected as containment spray pump and its motor drive. Failure Mode and Criticality Effects analysis is applied to evaluate the failure modes while the logic tree diagram used to determine the optimum maintenance strategy. It is concluded that condition based maintenance tasks should be enhanced to reduce component degradation and thus improve reliability and availability of the component. It is recommended to apply time directed tasks to age related failures and failure finding tasks to hidden failures.

Key Words : Reliability centered maintenance, Systems engineering, Value modeling, Failure Mode Criticality and Effect analysis.*

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1. Introduction

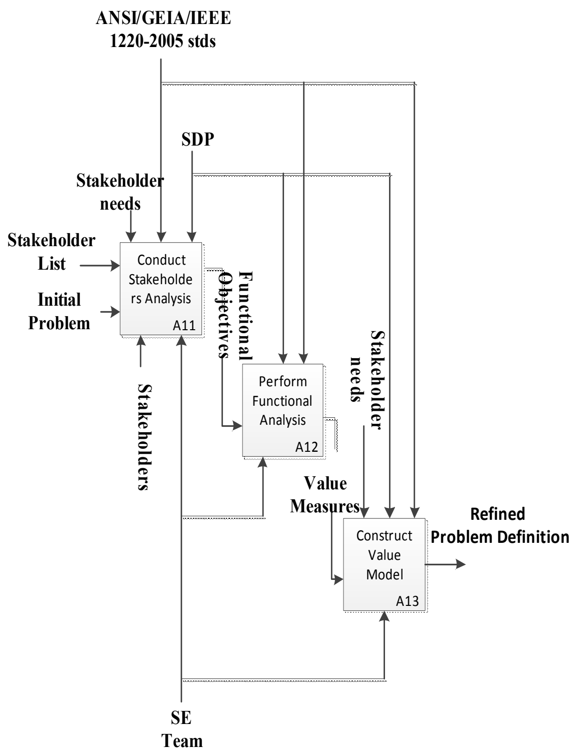
Improvement of safety related systems at a nuclear power plant has been one of the main concerns of the utility and regulatory body through nuclear power plant operation to achieve high safety levels in the event of design basis accidents. In order to maintain high reliability and availability of such components, a careful choice of maintenance strategy is desirable. There are many maintenance strategies that have been used to improve the health of assets in various industries. One such maintenance strategy is reliability centered maintenance (RCM). RCM has its roots in the airline industry where it has been used to tackle maintenance challenges for over 30 years now [2]. The RCM is now finding its way towards the nuclear industries and has been used mainly in normally operating systems [3].

However many standby systems have not had much of the RCM application in the nuclear industry despite their importance to safety. The containment spray system is one such safety system that is rarely used during normal operation and neglected by the maintenance personnel because of its location.

It is against this background that systems engineering approach is introduced to effectively address the challenges associated with the traditional strategy. This paper introduces the systems engineering process by defining the problem, needs analysis, concept development, trade off analysis and selection of the best maintenance strategy for the containment spray pump.

2. Problem definition

System decision making process assists stakeholders define their problem correctly before attempting to develop solutions. The functions of safety related components should be maintained so that in the event of design basis accidents, the provision of the mitigating functions would be assured. In order to clearly define the problem statement of this project, stakeholder analysis, functional analysis and value modeling are performed using IDEF0 level 1shown in figure 1.[4].



[Figure 1] IDEF0 Level 1 diagram for Problem definition

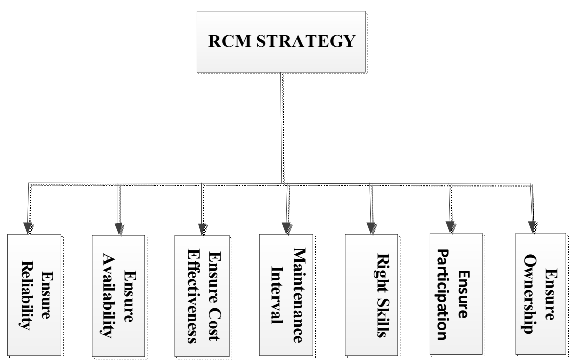
2.1 Stakeholders' research and analysis

<Table1> Stakeholders analysis

Technique	Ideal Stakeholder	Execution
Interviews	Managers	Conversation with the leaders
Surveys	PRA experts, Maintenance Engineers, Operation Engineers	Survey Questionnaires

Table 1 shows stakeholders analysis for the RCM application in the nuclear power plant. The needs of the stakeholders are solicited by using interviews and surveys. Interview technique is applied to the top management because it is more convenient to collect more information from this cadre of people using the interview technique. Survey technique is applied on the operations, maintenance, and probabilistic safety assessment staff because of large number and the information required is technical.

2.2 Value hierarchy



[Figure 2] Value Hierarchy for Maintenance Strategy

Figure 2 shows the attributes necessary for the implementation of the RCM strategy. These value measures are defined by the stakeholders as the most important needs that should be addressed in the maintenance strategy implementation.

2.3 Value modeling

The weights are allocated to value measures by the stakeholders in order of their importance as shown in table 2.

<Table 2> Swing weight matrix for effective RCM implementation

		Level of importance of the value measure		
		High	Medium	Low
Measure range	High	Reliability [95] [A]	Skills [85] [B2]	Communication [65] [C3]
	Medium	Availability [90] [B1]	Ownership [75] [C2]	Participation [50] [D2]

Allocation of weights in table 2 is applied using the following constraints;

A> all other cells

B1> C2, D2

B2> C2, C3, D2

C2> D2

C3> D2

<Table 3> Global weights of the value measures for the effective RCM implementation

No	Value Measures	Swing Weight	Measure Global Weight
1	Reliability	95	0.2065
2	Availability	90	0.1957
3	Skills	85	0.1849
4	Ownership	75	0.1630
5	Communication	65	0.1413
6	Participation	50	0.1087
	TOTAL	460	1

Table 3 illustrates how the global weight is obtained, by dividing the individual value measure' s weights by the total swing weight.

2.4 Sensitivity Analysis on Value Measures using chi-square method.

This analysis is used to verify the objectivity of the values allocated by the respondents to the importance measures (reliability, availability, skills etc.). Chi square tests any statistical hypothesis in which the sampling distribution of the test statistic, is a chi-squared distribution when the null hypothesis (Ho) is true. In this computation the null hypothesis assumes the survey results to be correct. A confidence level of 95% is chosen. This null hypothesis (Ho), is what the chi-square test attempts to prove.

<Table 4> Observed values from survey feedback

Measure range		Level of importance of the value measure		
		High	Medium	Low
	High	Reliability [16]	Skills [7]	Communication [9]
	Medium	Availability [11]	Ownership [4]	Participation [3]

The results of the stakeholders' survey are illustrated in table 4. The observed results show that 16 respondents classify reliability as high-high, 7 respondents classify skills as high-medium, communication (high-low), availability (medium-high), ownership (medium-medium) and participation(medium-low).

The target population of stakeholders is 50. The respondents are divided into two samples for ease of analysis. Sample 1 represents the respondents whose measure range is high while sample 2 represent respondents with medium measure range.

<Table 5> Observed values for sample 1

Measure range		Level of importance of the value measure		
		High	Medium	Low
	High	Reliability [16]	Skills [7]	Communication [9]

Table 5 shows sample' s 1 observed results from a population of 32 (16+7+9) respondents which corresponds to the high measure range.

<Table 6> Observed values for sample 2

Measure range		Level of importance of the value measure		
		High	Medium	Low
	Medium	availability [11]	Ownership [4]	Participation [3]

Table 6 shows the sample' s 2 observed results from a population of 18 respondents. This outcome corresponds to the medium measure range.

<Table 7> Chi square calculation

	High	Medium	Low		High	Medium	Low
High [observed] (0)	16	7	9	Medium [Observed]	11	4	3
Expected value(E)	(0.5) (32) =16	(0.3) (32) =9.6	(0.2) (32) =6.4	Expected value(E)	(0.5) (18) =9	(0.3) (18) =5.4	(0.2) (18) =3.6
(O−E)	0	−2.6	2.6		2	−1.4	−0.6
$(O-E)^2$	0	6.76	6.76		4	1.96	0.36
$(O-E)^2/E$	0	0.704	1.056		0.444	0.362	0.1
$\Sigma(O-E)^2/E$	$0+0.704+1.056+0.444+0.362=0.1=2.666=X^2$						

The expected value measures are divided into 50% for high level of importance, 30% for medium level of importance and 20% for low level of importance. These weights are used in the computation of the expected value E by multiplying expected value measure by two samples as shown in the second row of table 7. Observed value O is derived from tables 5 and 6. Using chi square formula in the last row of table 7, a Chi- Square statistic = X2= 2.666 is obtained.

In order to use the Chi square distribution table, degree of freedom is calculated using the following formula ;

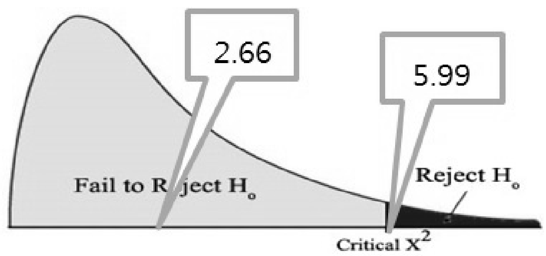
Degree of freedom = df = (Row−1)(Column 1) = (2−1) (3−1) =2

Where row and column refer to 2x3 matrix as shown in table 4 and the confidence level is 95% which translates to α =0.05.

<Table 8> Chi-square distribution table

α =	0.995	0.99	0.98	0.975	0.95	0.90	0.80	0.20	0.10	0.05
V = 1	0.0000393	0.000157	0.000628	0.000982	0.00393	0.0158	0.0642	1.642	2.706	3.841
2	0.0100	0.0201	0.0404	0.0506	0.103	0.211	0.446	3.219	4.605	5.991
3	0.0717	0.115	0.185	0.216	0.352	0.584	1.005	4.642	6.251	7.815
4	0.207	0.297	0.429	0.484	0.711	1.064	1.649	5.989	7.779	9.488
5	0.412	0.554	0.752	0.831	1.145	1.610	2.343	7.289	9.236	11.070

Using the Chi-Square Distribution Table 8 and the values of freedom and confidence level, a critical value = Xc2 = 5.99 is obtained.



<Figure 3> Chi- square curve

Figure 3 shows a chi-square curve with the chi-square value 2.66 lying on the acceptance area. This result verifies the data as goodness of fit and the null hypothesis proved correct. This is the justification for the weight allocation as shown in table 2.

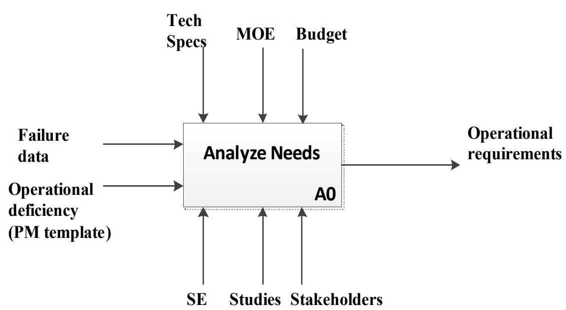
2.5 Refined problem definition

From the analysis above, the maintenance strategy for the safety related components should provide reliability performance criterion of 1 failure in 2 refueling periods [3yrs] and availability of more than 97.5% while ensuring Plant safety. The maintenance strategy should be cost effective and develop required skills for its implementation. The implementation process must ensure participation and ownership by key stakeholders (Utility).

3. Concept development

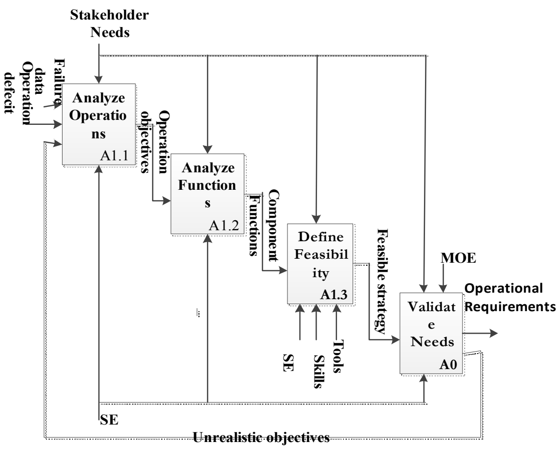
3.1 Needs analysis

The needs analysis is a phase that is responsible for the determination of the need or desire for a new system. In this study the application of reliability centered maintenance strategy on containment spray pump in a nuclear power plant is evaluated. This is done using Integrated Definition Function model IDEF0 to show the activities involved in the needs analysis phase as shown in figure 3.



[Figure 4] IDEF0 Level 0 diagram for Needs analysis

The needs analysis process can be decomposed into smaller activities in order to understand the process and the interrelationship between the inputs, enablers, controls and output. The decomposition is shown using figure 5.



[Figure 5] IDEF0 Level 1 diagram for Needs analysis

3.1.1 Operational objectives

Many maintenance strategies have been developed and used in both service and nuclear industries. The use of traditional preventive maintenance and corrective maintenance that is time directed have led to performance of some tasks that are not critical and in equal measures some important tasks have been ignored. The following are some of the operational objectives that will be expected to be provided by RCM :

- To provide high component reliability
- To reduce component failure rate
- To reduce the maintenance cost
- To reduce the maintenance intervals

3.1.2 Functional analysis

In this phase the possibility of developing a strategy that fulfills the operational objectives is evaluated. The operational objectives are translated into functional requirements. The functions to be performed by each stakeholder in implementing RCM are allocated at this phase. Visualizing all required data and materials to perform RCM process.

3.1.3 Feasibility definition

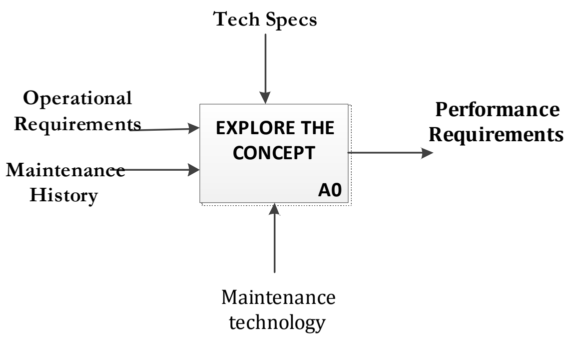
The feasibility of the new maintenance strategy is evaluated on the basis of the cost effectiveness and the availability of the necessary skills to effectively implement the proposed new maintenance strategy. The outcome of this process is a more refined, feasible strategy capable of being implemented by the concerned utility.

3.1.4 Needs validation

The validity of the process is evaluated on the basis of cost implication and the performance of the strategy. The benefits accrued from the proposed maintenance strategy will only be realized if the utility can afford the cost of implementation. Therefore there is need to re−evaluate the stakeholders operational objectives and select only the realistic objectives. The output of this process is operational requirements to be passed on to the next stage of concept exploration for further analysis.

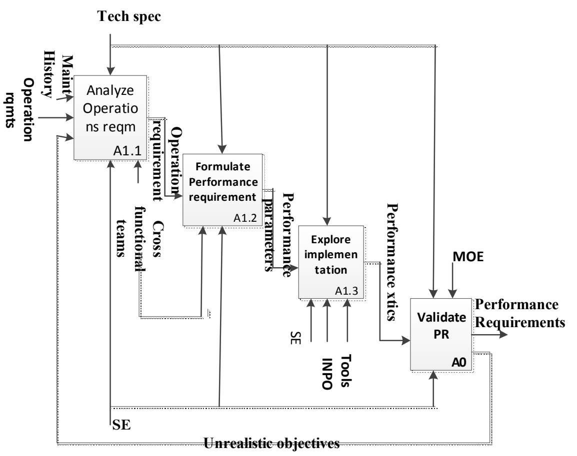
3.2 Concept exploration

This is the phase of concept development where the various solution candidates or alternatives are discussed and evaluated in order to meet the operational requirements. The principal objective of the concept exploration phase is to convert operational objectives into engineering oriented concept that would explicitly provide basis for selecting an acceptable functional and physical system concept. The analysis of concept exploration can be illustrated using the IDEF0 level 0 shown in the figure below:



[Figure 6] IDEF0 Level 0 diagram for Concept Exploration

The activities performed in concept exploration can be decomposed further into sub−functions to enhance the understanding the interactions involved in terms of inputs, enablers, controls and outputs. This decomposition is shown in the figure below :



[Figure 7] IDEF0 Level 1 diagram for Concept Exploration phase

3.2.1 Operational requirements analysis

This step evaluates the completeness and consistency of the operational requirements. It uses the initial set of operational requirements, an operation concept of the RCM and the operational scenario showing the environment of operation of the system. The operational objectives are refined as below :

- To allow only one component failure in three years
- To provide above 97.5% component availability
- To reduce the maintenance cost
- To increase the maintenance intervals from 18months to 20months

The requirement elicitation would be obtained from the following sources :

- FSAR
- Operations personnel
- Maintenance personnel
- Safety expert
- I&C expert

The output of the process is a set of well evaluated operational requirements.

3.2.2 Performance requirement analysis

This analysis is concerned with what to be performed and by how much to perform the functions in order to achieve or satisfy the operational requirements. In attempting to satisfy the operational requirement for the maintenance strategy, many options can be proposed from which the best alternative should be chosen. The output of this process is performance parameters.

3.2.3 Implementation of concept exploration

This process explores a wide range of maintenance alternatives and carries out SWOT analysis and assesses the performance, risk, cost and adaptability of the alternatives in terms of the skills required. The various functional failure modes will require that the following maintenance strategies are explored in terms of why, how, when, who and where they can be applied ;

- Condition directed task
- Time directed tasks
- Functional Failure Finding tasks
- Run to Failure or corrective maintenance tasks

3.2.4 Performance requirements validation

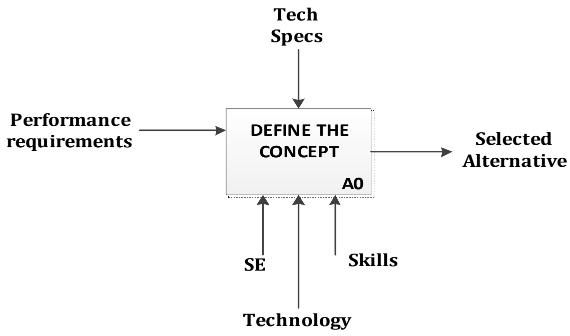
This is done by integrating the requirements derived from the alternative candidate solutions and their effectiveness to meet the stated operational requirements. If there is any over stated operational requirement, then it is fed back to the operational analysis for re-evaluation since the available maintenance strategies may not be able to meet the operation requirements.

3.3 Concept definition

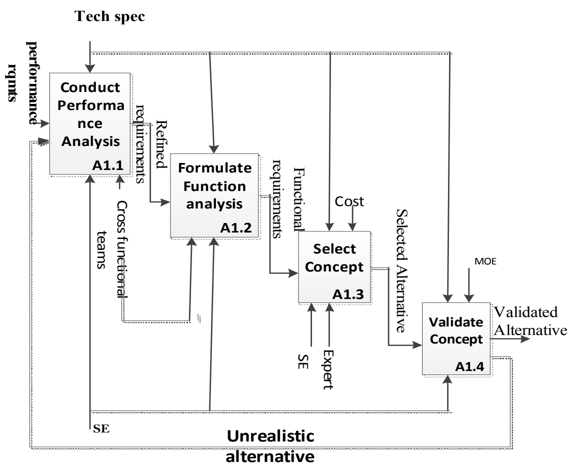
This phase marks the beginning of serious work of defining the functional and physical characteristics of RCM. The selected maintenance strategy is supposed to meet all the refined operational needs as described in the preceding conceptual phases. At this stage a number of specialty engineers are added onto the project team to boost the implementation of the selected maintenance strategy. The process is described using an IDEF0 Level 0 diagram shown in figure 8.

The concept definition phase can be decomposed into smaller processes to make it easier to understand the interaction and interrelations.

- Performance Requirement analysis
- Functional analysis
- Concept selection
- Concept validation

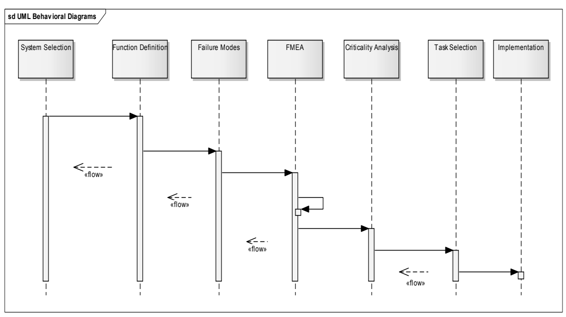


[Figure 8] IDEF0 Level 0 diagram for Concept Definition phase



[Figure 9] IDEF0 Level 1 diagram for Concept Definition phase

4. Design of reliability centered maintenance process



[Figure 10] Sequence diagram for RCM process

The RCM process involves the system selection in which the system of interest is chosen. Functions of the selected system are defined and the possible failure modes of the system that can lead to the failure of the system to fulfill its functions are outlined. The Failure Mode and effects analysis is then done and this helps in the identification of the dominant failure modes and the outlines the consequences of the failure modes on the system and plant level. Criticality analysis is then carried out to categorize the failure modes according to their criticality to safety, availability, and maintenance cost. The RCM process ends with the selection of the maintenance task for the component.

4.1 System selection

The system of study was selected based on the results from PSA for OPR 1000. Table 9 shows the ranking of the importance measures (Risk Achievement worth, Risk Reduction Worth). In table 9, the pump has the greatest, RAW and RRW and therefore the most critical component in the containment spray system [6].

<Table 9>important measures ranking

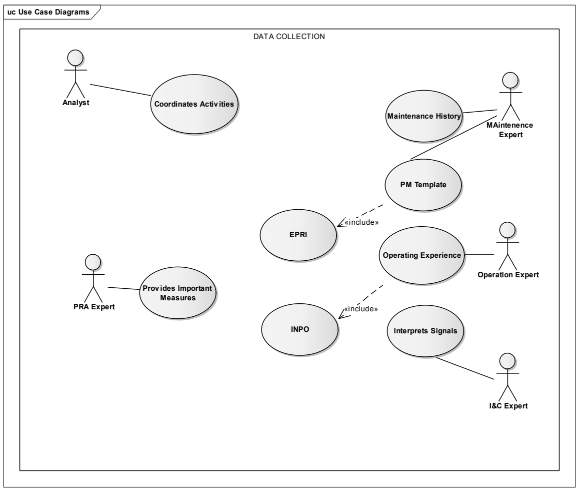
Event	RAW	RRW
CSXPRA-CSPUMP	1.0300	1.0007
CSMV01A-003	1.0200	1.0000
CSMV01B-004	1.0200	1.0000
CSHEM2A-HE01A	1.0100	1.0000

4.2 Data collection

The data used for this study is collected through the following ways ;

- Maintenance history from maintenance personnel
- Operating experience from the operations staff
- Probabilistic Safety Assessment results from PRA experts
- Review of INPO and EPRI documentation
- Instrumentation and Control expert(trip signals)

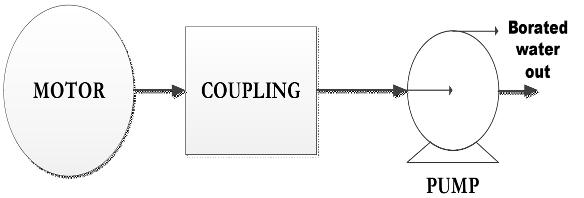
The data collection process is presented using USE CASE diagram to give a clear understanding of the interactions involved in the information gathering by various stakeholders.



[Figure 11] USE CASE diagram for data collection

4.3 System boundary

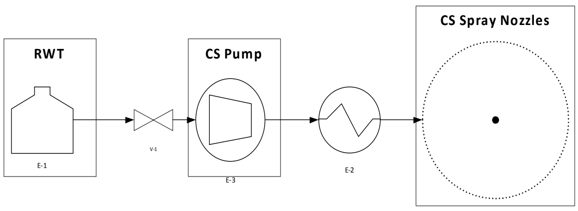
The system of interest consists of the pump and the drive motor. This is illustrated in figure 12. The pump consists of the impeller, shaft, coupling, bearings, casing, mechanical seals, O-rings while the motor consists of the rotor and the stator.



[Figure 12] System boundary

4.4 System functions and functional failures

- Provides Cooling and depressurizing the containment atmosphere after the accident.
- Provides a backup to the Shutdown Cooling pump when it is unavailable



[Figure 13] Functional Block diagram for the CS system

4.5 Root cause and failure analysis

The potential causes of the failures on the components are evaluated in detail for each failure mode. The root cause analysis for the pump and the motor drive forms the input for the criticality analysis. The analysis is shown in table 10.

4.6 Failure mode and effect analysis

Failure Mode and effect analysis is a technique used to identify the potential functional failures, the effects of those failures on system, evaluates risk priority numbers for the failure modes, and suggests possible remedial measures to prevent identified problems. The failure mode and effect analysis is tabulated in table 11.

4.7 Criticality analysis for the pump components

The criticality analysis is based on the effects of the failure modes on the plant's safety, availability and maintenance cost. The safety aspect is allocated a weight of 50%, since in nuclear power plant; safety is the most important factor. Availability of the safety component to sustain production of full power is assigned 30% and the cost incurred by such failures has a weight of 20%. The value ranging from 1-4 is then allocated to the failure causes depending on their severity on safety, availability and maintenance cost. The ranking is based on the expert judgment and operating experience on the failure modes consequences [8]. Criticality analysis is carried out in table 13.

Severe to safety : If the failure mode induces a loss of vital safety function

Severe to availability/production : If the failure induces a shutdown or reduction in the power level.

Severe to maintenance : If the failure mode leads to costly repairs

Not severe : If the failure mode does not lead to any severity to safety, availability or maintenance costs.

$$EC=0.5S+0.3A+0.2C \quad [1]$$

4.8 Task selection

The maintenance tasks are selected based on the failure mode impact on safety, availability, economic and whether the failures are hidden or evident to operator [9]. Table 14 shows the task selection process.

<Table 10> Root Cause analysis for CS pump

Item	Failure Mechanism	Root cause
Impeller	– Low flow rate	① Vane thinning, ② wear vortexing
	– Low discharge pressure	① Loose or failed key
	– No liquid delivery	① Damage by debris
	– High vibration at impeller	① Wear– cavitation ② Rubbing–motor thrust ③ Face/shroud rubbing
Bearings–Anti–Friction	High bearing temperature	① Wear– fatigue– age ② Wear– fatigue–misalignment ③ Wear– fatigue– excessive loading ④ Wear– fatigue– personnel error
Kingsbury Bearings	High bearing temperature	① Wear– incorrect lubricant ② Wear– insufficient lubricant ③ Wear– insufficient lubricant ④ Wear– excessive oil Wear– electric current
Rotor	Rotor not turning	① Loose lamination ② Failed rotor band/shorting rings ③ Rotor/stator mechanical interface problem ④ Loose retaining rings ⑤ Loose rotor cage
Stator	Very high temperature	① Insulation breakdown of lamination ② Contaminated laminations ③ Winding insulation degradation ④ Winding insulation degradation from corona ⑤ Loose blocking & bracing
Motor leads	High electrical resistance	① Degraded insulation
Electrical connections	Arcing	① High resistance ② Degraded insulation
Gasket & O–Rings	Leakages	① Corroded– wrong materials ② Degraded– aging ③ Improper installation ④ High temperature
Pump/Motor coupling	High vibration at coupling	① Improper fit ② Imbalance ③ Damaged adjustment nut’ plate
Mechanical Seal	Leakages	① Worn out seals
Shaft		① Cracked ② Whip, off BEP ③ Shaft wear Bent shaft

<Table 11> Failure Mode and Effect analysis for CS pump

Item	Failure Mode	Effect on Pump	Effect on System	Effect on Plant
Impeller	Vane thinning,	Low efficiency	Entry into LCO	Power reduction
	wear vortexing	Low efficiency	Entry into LCO	Power reduction
	Loose or failed key	Suction pressure reduction	System NPSH low	Power reduction
	Damage by debris	No discharge flow	No system flow	Power reduction
	Wear- cavitation	Low efficiency	Entry into LCO	Power reduction
	Rubbing-motor thrust	Vibration	System NPSH low	Power reduction
	Face/shroud rubbing	Vibration	System NPSH low	Power reduction
Bearings-Anti-Friction	Wear- fatigue- age	Low efficiency	Entry into LCO	Power reduction
	Wear- fatigue-misalignment	Excessive pump vibration	System NPSH low	Power reduction
	Wear- fatigue- excessive loading	Pump shutdown	No system flow	Power reduction
	Wear- fatigue- personnel error	Pump shutdown	No system flow	Power reduction
Kingsbury Bearings	Wear- incorrect lubricant	Pump corrosion	Low system flow	Power reduction
	Wear- insufficient lubricant	Pump overheating(adhesive wear)	Low system flow	Power reduction
	Wear- excessive oil	Pump failure due grease churning	No system flow	Power reduction
	Wear- electric current	Pump motor malfunction	No system flow	Power reduction
Rotor	Loose lamination	Low motor efficiency	Low system flow	Power reduction
	Failed rotor band/shorting rings	Motor shutdown	No system flow	Power reduction
	Rotor/stator mechanical interface problem	Noise and vibration on the motor	Low system flow	Power reduction
	Loose retaining rings	Motor leakages	Low system flow	Power reduction
	Loose rotor cage	Noise and vibration on the motor	Low system flow	Power reduction

Item	Failure Mode	Effect on Pump	Effect on System	Effect on Plant
Stator	Insulation breakdown of lamination	Motor short circuit Motor over−heating	No system flow	Power reduction
	Contaminated laminations		No system flow	Power reduction
	Winding insulation degradation	Motor over−heating	No system flow	Power reduction
	Winding insulation degradation from corona	Motor over−heating	No system flow	Power reduction
	Loose blocking & bracing	Motor noise & vibration	No system flow	Power reduction
Motor leads	Degraded insulation	Motor fails to start	No system flow	Power reduction
Electrical connections	High resistance	Low motor motive force	No system flow	Power reduction
	Degraded insulation	Motor fails to start	No system flow	Power reduction
Gasket & O−Rings	Corroded− wrong materials	Pump internal liquid leakage	Low system flow	Power reduction
	Degraded− aging	Pump capacity greatly reduced	Low system flow	Power reduction
	Improper installation	Eminent impeller wear	Low system flow	Power reduction
Pump/Motor coupling	Improper fit	Loss of pumping efficiency	Low system flow	Power reduction
	Imbalance	Possible seals damage	Low system flow	Power reduction
	Damaged adjustment nut' plate	Noise and vibration on the pump	Low system flow	Power reduction
Mechanical Seal	Worn out seals	Loss of pumping efficiency Leakages	Low system flow	Power reduction
Shaft	Cracked	Pump low efficiency	Low system flow	Power reduction
	Whip, off BEP (Best efficiency point)	Possible bearing damage	Low system flow	Power reduction
	Shaft wear	Increase in shaft radial movement	Low system flow	Power reduction
	Bent shaft	Vibration Eventual coupling failure	Low system flow	Power reduction
Casing	Leaking casing	− Reduction in pumping rate − Possible corrosion on all pump components	Low system flow	Power reduction

<Table 11> Level of importance

Criteria	Unit	Weight	Level
Effect on Safety	S	50%	[1]Less critical [2]Moderately critical [3]Critical [4]Very Critical
Effect on Availability	A	30%	1]Less critical [2]Moderately critical [3]Critical [4]Very Critical
Effect on Maintenance costs	C	20%	[1]Low [2]Moderate [3]High [4]Very High

Table 11 shows the weight allocation to each criterion and the level of importance attached to them. Very critical implies that the effect of failure mechanism on the criterion is high while less critical means the impact on criterion is negligible. The ranking level 4 shows higher impact on the criterion as compared to rank level 1.

<Table 12> Criticality analysis

Category	Measure of Criticality
Q	4.0−3.0
R	3.0−2.0
S	2.0−1.5
T	1.5−1.0

Table 12 illustrates the criticality classes Q to R in the first column and the criticality index on the second column. The measure of criticality is calculated using formula [1]. These values are used to determine the type of maintenance task to be applied on each failure mode.

<Table 13> Criticality analysis for containment spray pump

Item	Failure Mode	Safety	Availability	Cost	MOC	Class	Description
Impeller	Vane thinning,	4	4	3	3.8	Q	Measure pump head
	wear vortexing	4	4	3	3.8	Q	Measure impeller vibration
	Loose or failed key	4	4	2	3.6	Q	Measure pump head
	Damage by debris	4	4	4	4.0	Q	Re-design by adjusting strainer position
	Wear-cavitation	4	4	4	4.0	Q	Measure pump flow rate
	Rubbing-motor thrust	4	4	3	3.8	Q	Measure impeller vibration
	Face/shroud rubbing	4	4	3	3.8	Q	Measure impeller acoustic level
Bearings-Anti-Friction	Wear- fatigue-age	4	3	2	3.3	Q	Measure pump bearing vibration
	Wear-fatigue-misalignment	4	3	2	3.3	Q	Measure vibration+acoustics
	Wear- fatigue-excessive loading	4	3	2	3.3	Q	Measure loading+ vibration
	Wear- fatigue-personnel error	4	4	2	3.6	Q	Check the training needs
Kingsbury Bearings	Wear- incorrect lubricant	4	3	2	3.3	Q	Measure pump motor oil contamination level
	Wear-insufficient lubricant	4	4	2	3.6	Q	Measure pump motor vibration+acoustics
	Wear- excessive oil	4	4	2	3.6	Q	Measure vibration+acoustics
	Wear- electric current	4	4	2	3.6	Q	Measure vibration+acoustics
Rotor	Loose lamination	4	4	4	4.0	Q	Measure winding temp
	Failed rotor band/shorting rings	4	4	4	4.0	Q	Measure circuit resistance
	Rotor/stator mechanical interface problem	4	3	2	3.3	Q	Measure vibration+acoustics
	Loose retaining rings	4	2	1	2.8	R	Replace rings
	Loose rotor cage	4	2	1	2.8	R	Replace cages
Stator	Insulation breakdown of lamination	4	4	4	4.0	Q	Measure stator insulation

Item	Failure Mode	Safety	Availability	Cost	MOC	Class	Description
	Contaminated laminations	4	4	4	4.0	Q	Failure finding task
	Winding insulation degradation	4	4	4	4.0	Q	Measure winding temperature+ PI level
	Winding insulation degradation from corona	4	4	2	3.6	Q	Measure winding temperature+ FFT of current
	Loose blocking & bracing	4	3	2	3.3	Q	Tighten/Replace block
Motor leads	Degraded insulation	4	4	1	3.4	Q	Measure winding temperature+ FFT of current
Electrical connections	High resistance	3	4	2	3.1	Q	
	Degraded insulation	4	4	1	3.4	Q	Measure insulation & PI level
Gasket & O-Rings	Corroded- wrong materials	4	4	1	3.4	Q	Replace gaskets/ rings
	Degraded- aging	4	4	1	3.4	Q	Measure vibration+acoustics
	Improper installation	4	4	1	3.4	Q	Failure finding task
Pump/Motor coupling	Improper fit	4	4	2	3.6	Q	Measure vibration+acoustics
	Imbalance	4	4	2	3.6	Q	Measure vibration+acoustics
	Damaged adjustment nut' plate	4	3	1	3.1	Q	Measure vibration+acoustics
Mechanical Seal	Worn out seals	4	4	3	3.8	Q	Measure oil level
Shaft	Cracked	4	4	3	3.8	Q	Measure vibration+acoustics
	Whip, off BEP (Best efficiency point)	4	4	1	3.4	Q	Measure vibration+acoustics
	Shaft wear	4	4	2	3.6	Q	Measure vibration+acoustics
	Bent shaft	4	4	3	3.8	Q	Measure vibration+acoustics
Casing	Leaking casing	3	4	3	3.8	Q	Measure oil level

Table 13 shows the computation of measures of criticality for the pump' s failure mechanisms. A value of 4.0 shows a highly critical failure mode whose degradation should be monitored closely. A value of between 1.5-1.0 indicates a less significant failure mode that can be run to failure.

<Table 14> Task selection

Item	Failure Mode	Class	Selected Task	Monitoring Parameters
Impeller	Vane thinning,	Q	Condition directed [Vibration analysis]	Measure pump head
	wear vortexing	Q	Condition directed [Vibration analysis]	Measure impeller vibration
	Loose or failed key	Q	Condition directed [Vibration analysis	Measure pump head
	Damage by debris	Q	Re-design	Change strainer location
	Wear-cavitation	Q	Condition directed [Vibration analysis	Measure pump flow rate
	Rubbing-motor thrust	Q	Condition Directed [vibration analysis]	Measure impeller vibration
	Face/shroud rubbing	Q	Condition directed [Airborne acoustic analysis]	Measure impeller acoustic level
Bearings-Anti-Friction	Wear- fatigue- age	Q	Condition directed [vibration analysis	Measure bearing casing vibration
	Wear-fatigue-misalignment	Q	Condition directed [vibration analysis+ Airborne acoustic analysis]	Measure bearing casing vibration+acoustics level
	Wear- fatigue-excessive loading	Q	Condition directed [vibration analysis]	Measure loading+ vibration
	Wear- fatigue-personnel error	Q	Failure finding	Check personnel training level.
Kingsbury Bearings	Wear- incorrect lubricant	Q	Condition directed [Lubrication analysis]	Measure oil bearing contamination level
	Wear- insufficient lubricant	Q	Condition directed [vibration analysis+ Airborne acoustic analysis]	Measure vibration+acoustics
	Wear- excessive oil	Q	Condition directed [vibration analysis+ Airborne acoustic analysis]	Measure vibration+acoustics
	Wear- electric current	Q	Condition directed [vibration analysis+ Airborne acoustic analysis]	Measure vibration+acoustics
Rotor	Loose lamination	Q	Condition directed [Infrared-Thermography + Motor current signature]	Measure winding temp
	Failed rotor band/shorting rings	Q	Condition directed [Infrared-thermography +motor current signature	Measure circuit resistance

Item	Failure Mode	Class	Selected Task	Monitoring Parameters
	Rotor/stator mechanical interface problem	Q	Condition directed [Infrared−thermography +vibration analysis]	Measure vibration+acoustics
	Loose retaining rings	R	Time directed task[Scheduled restoration]	Replace rings
	Loose rotor cage	R	Time directed task[scheduled tightening]	Replace cages
Stator	Insulation breakdown of lamination	Q	Condition directed [Infrared−Thermography + motor current signature+motor circuit analysis]	Measure stator insulation
	Contaminated laminations	Q	Failure Finding Task	FF
	Winding insulation degradation	Q	Condition directed [Infrared−Thermography + motor current signature+motor circuit analysis]	Measure winding temperature+ PI level
	Winding insulation degradation from corona	Q	Condition directed [Infrared−Thermography + motor current signature+motor circuit analysis]	Measure winding temperature+ FFT of current
	Loose blocking & bracing	Q	Time directed task[Scheduled restoration]	Tighten/Replace block
Motor leads	Degraded insulation	Q	Condition directed [Infrared−Thermography + motor current signature+motor circuit analysis]	Measure winding temperature+ FFT of current
Electrical connections	High resistance	Q	Condition directed [Infrared−thermography]	Measure temperature of connections.
	Degraded insulation	Q	Condition directed [Infrared−Thermography + motor current signature+motor circuit analysis]	Measure insulation & PI level
Gasket & O−Rings	Corroded− wrong materials	Q	Time directed task[Scheduled restoration]	Replace gaskets/ rings
	Degraded− aging	Q	Condition directed [Airborne acoustic analysis+vibration analysis]	Measure vibration+acoustics
	Improper installation	Q	Failure finding	Check personnel training level.
Pump/Motor	Improper fit	Q	Condition directed	Measure vibration+acoustics

Item	Failure Mode	Class	Selected Task	Monitoring Parameters
coupling			[Vibration analysis+ Airborne acoustics+Infra-red thermography]	
	Imbalance	Q	Condition directed [Vibration analysis+ Airborne acoustics]	Measure vibration+acoustics
	Damaged adjustment nut' plate	Q	Condition directed [Vibration analysis+ Airborne acoustics]	Measure vibration+acoustics
Mechanical Seal	Worn out seals	Q	Condition directed [Airborne acoustic analysis	Measure oil level
Shaft	Cracked	Q	Condition directed [Vibration analysis+ Airborne acoustics	Measure vibration+acoustics
	Whip, off BEP (Best efficiency point)	Q	Condition directed [	Measure vibration+acoustics
	Shaft wear	Q	Condition directed [Vibration analysis+ Airborne Acoustics]	Measure vibration+acoustics
	Bent shaft	Q	Condition directed [Vibration analysis+ Airborne acoustics]	Measure vibration+acoustics
Casing	Leaking casing	Q	Condition directed [Airborne acoustic analysis	Measure oil level

5. Conclusion

The criticality analysis shows that most of the pump failure modes can be monitored using condition based techniques. These tools detect and trend the degradation indicators before the potential failure occurs. The trended results are used to carry out maintenance on the components before failure. RCM increases the mean time before failure of component and consequently improved availability. The proposed maintenance strategies reduce the number of periodic maintenance activities and therefore save the maintenance cost.

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