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Application of Reliability Centered Maintenance Strategy to Safety Injection System for APR1400

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Abstract : Reliability Centered Maintenance (RCM) introduces a systematic method and decision logic tree for utilizing previous operating experience focused on reliability and optimization of maintenance activities. In this paper RCM methodology is applied on safety injection system for APR-1400. Functional Failure Mode Effects and Criticality Analysis (FME&CA) are applied to evaluate the failure modes and the effect on the component, system and plant. Logic Tree Analysis (LTA) is used to determine the optimum maintenance tasks. The results show that increasing the condition based maintenance will reduce component failure and improve reliability and availability of the system. Also the extension of the surveillance test interval of Safety Injection Pumps (SIPs) would lead to an improved pump's availability, eliminate the unnecessary maintenance tasks and this will optimize maintenance activities.

Key Words : KEYWORDS: Reliability Centered Maintenance, Safety Injection System, APR-1400

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1. Introduction

Reliability-Centered Maintenance is the methodology of determining the most effective maintenance plan. It employs Preventive Maintenance, Predictive Maintenance, Real-time Monitoring, Run-to-Failure and Proactive Maintenance techniques independently and in an integrated manner to increase the probability that a component will function in the required manner over its operation life cycle with a minimum of maintenance activities [1].

1.1 Basis of RCM process

Reliability centered maintenance is defined as a systematic evaluation approach for developing or optimizing a maintenance programme. RCM utilizes a decision logic tree to identify the maintenance requirements of equipment according to the safety and operational consequences of each failure and the degradation mechanism responsible for the failures, focus on the system functions only [2]. The RCM process involves:

- System selection and system boundary.
- Identify the possible failure modes that could lead to the failure of the system to fulfill its functions.
- Perform failure mode effects (FME).
- Perform criticality analysis to calculate the severity of each failure mode with respect to safety, availability, and maintenance cost.
- Selection of the maintenance task using Logic Tree Analysis (LTA).
- Compare the new tasks with the current tasks and implementation of the process [2].

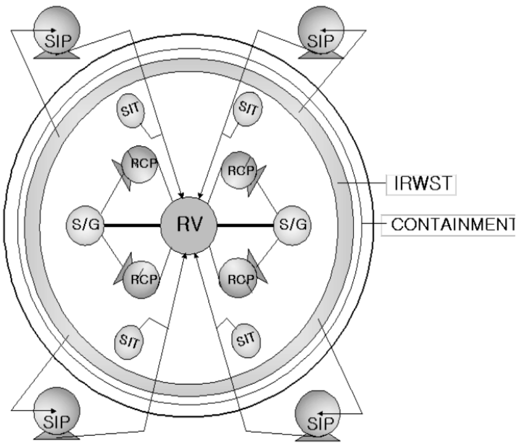
1.2 Objectives of the study

In this study RCM implementation process will be applied on the safety injection system for APR1400, the techniques of Functional Failure Mode Effects and Criticality Analysis (FME&CA) is applied to evaluate the different possible failure modes and the effect on component, system, and plant overall. Logic Tree Analysis (LTA) is used to determine the optimum maintenance tasks suitable for each failures modes according to the criticality class of each possible failure mode for the critical component.

2. Safety injection system

Safety Injection System is one of the engineered safety features (ESF) systems which provide protection in the highly unlikely event of an accidental release of radioactive fission products from the Reactor Coolant System (RCS), particularly as the result of a Loss Of Coolant Accident (LOCA). The safety features function to localize, control, mitigate, and terminate such incidents and to hold exposure levels below applicable limits [3].

The safety injection system is comprised of four independent mechanical trains without any tie line among the injection paths and two electrical divisions. Each train has one active Safety Injection Pump (SIP) and one passive Safety Injection Tank (SIT) equipped with a Fluidic Device (FD). Figure 1 shows system arrangement, each train provides 50% of the minimum injection flow rate for breaks larger than the size of a direct vessel injection line. For breaks equal to or smaller than the size of a direct vessel injection line, each train has 100% of the required capacity. The low pressure



RCP: Reactor Coolant Pump, S/G: Steam Generator
RV: Reactor Vessel, IRWST: In containment Refueling Water Storage Tank

[Figure 1] Safety Injection system arrangement

injection pumps with common header installed in the conventional design are eliminated, and the functions for safety injection and shutdown cooling are separated [3-4].

3. Systems engineering process

Systems engineering process is a structured way of thinking about and defining a system. The systems engineering process is an iterative approach to technical management, acquisition and supply, system design, product realization, and technical evaluation at each level of the system, beginning at the top (the system level) and propagating those processes through a series of steps which eventually lead to a preferred system solution [5].

3.1 Problem definition

The role of systems engineering is to define the problem correctly before seeking for solutions. The functions of safety related systems should be maintained so that in the event of design basis accidents, the provision of the mitigating functions would be assured. In preventive maintenance the failures are still likely to occur, the component may be over maintained, this leads to increase the interfaces with the component, in such unneeded maintenance there are chances of components incidental damage.

3.2 Problem solution

To increase the availability of the components and systems, the reliability centered maintenance is effective.

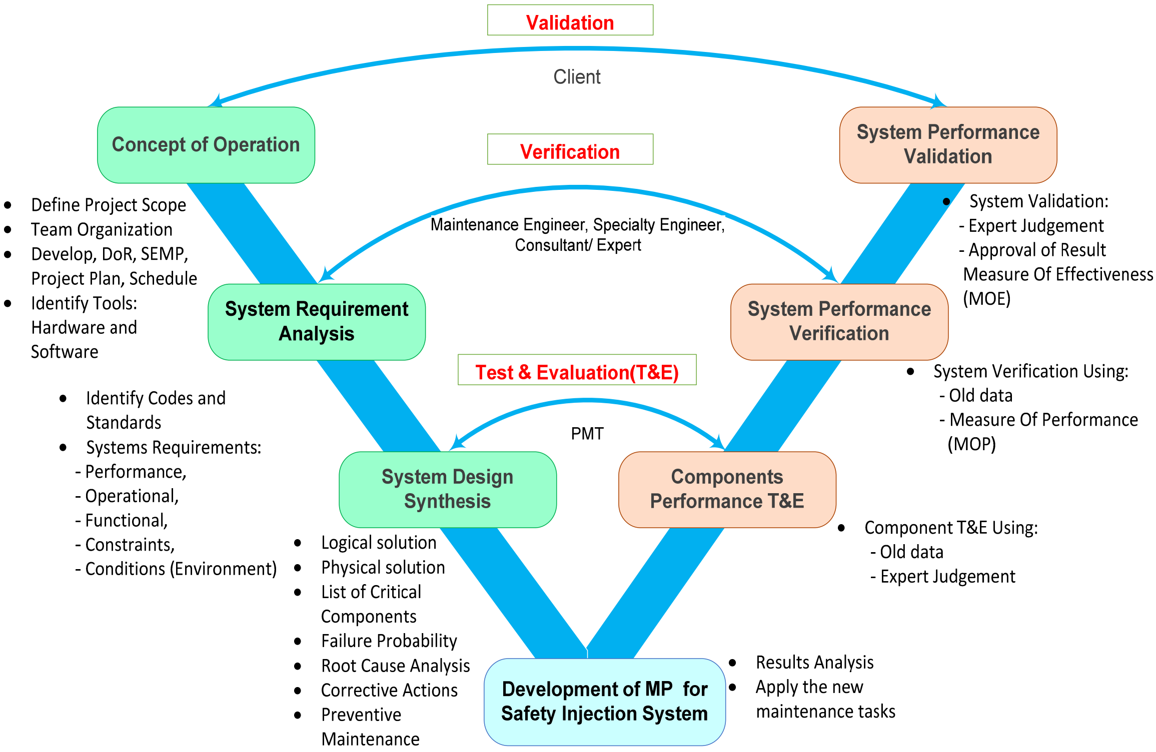
Because Condition Based Maintenance (CBM), focuses in system functions and use operation experience to analyze the failure modes effect and criticality analysis (FME&CA) techniques. RCM can increase the condition monitoring tasks and reduce the system maintenance activities and interfaces to increase the availability and reliability of the system [2].

3.3 V-Model

V-model will be used in the Study execution because it ensures a maximum transparency for both project parties. It is a systematic approach to understand project requirements of the client and maps these requirements to process definitions. The V-model also performs reviews on multiple levels tracing all customer requirements through the entire project life cycle so as to ensure clear and unambiguous requirements. Figure 2 shows the V-Model that shall be used in the study [5].

3.3.1 Concept of Operation

In this step, stakeholders prepare the maintenance methodology that maintains the reliability



[Figure 2] the V-Model

of Safety Injection System (SIS). They reach a shared understanding of the system to be developed and how it will be operated and maintained. The concept of operations is documented to provide a foundation for more detailed analyses that will follow. It will be the basis for the system requirements that are developed in the next step.

3.3.2 System Operational Requirements

The objectives of this step is to develop a validated set of requirements that meet the stakeholders' needs, use of traditional time directed maintenance did not focus in the critical tasks and some important tasks have been ignored, the maintenance strategy re-quirements are:

- The maintenance strategy should increase the Mean Time To Failure (MTTF).
- The maintenance strategy should reduce the component failure rate.
- The maintenance strategy should maintain inherent component reliability.
- The maintenance strategy should increase components and systems availability.
- The maintenance strategy should reduce the maintenance cost.
- The maintenance strategy should increase the surveillance testing intervals.
- The maintenance strategy should reduce the system interfaces.

The operational requirements are evaluated with control of the technical specifications of the system of interest. The output is a set of refined operational requirements which are complete and consistent.

3.3.3 Functional Analysis

In this step, the possibility of developing a strategy that fulfills the operational objectives is evaluated. The systems engineers can use RCM studies and applications on the system of interest as a basis of evaluating the functions to be performed. Maintaining the plant safety is the most important factor to this process. The operational objectives are translated into functional requirements. The functional requirements to be performed by RCM are:

- The maintenance strategy should maintain plant's general safety.
- The maintenance strategy should optimize the maintenance activities.
- The maintenance strategy should maintain component and system reliability and availability when demanded.
- The maintenance strategy should achieve cost effectiveness.

3.3.4 System Design

In this step, system design is created based on the system requirements including a high-level design that defines the overall framework for the system. Subsystems of the system are identified and decomposed further into components. Requirements are allocated to the system components, and interfaces are specified in detail, produce a high-level design that meets the system requirements and defines key interfaces, that facilitates development, integration, and future maintenance and upgrades. Previous steps in "V-model" have all focused primarily on defining the problem to be solved. The system design step is the first step where we focus on the solution. This is an important transitional step that links the system requirements that were defined in the previous step with system implementation that will be performed in the next step. The objective is to produce a high-level design that meets the system requirements and defines key interfaces, that facilitates development, integration, and future maintenance and upgrades.

Figure 3 shows the RCM process designed for SIS. The Work Breakdown Structure (WBS) and activities to be done during each phase are shown in the figure.

3.3.5 System Integration

In this step, the preparation of the new maintenance tasks selected for the critical components in the system are done. The objectives of this step are:

- Increase availability, reliability and safety of the system.
- Optimize the maintenance program.

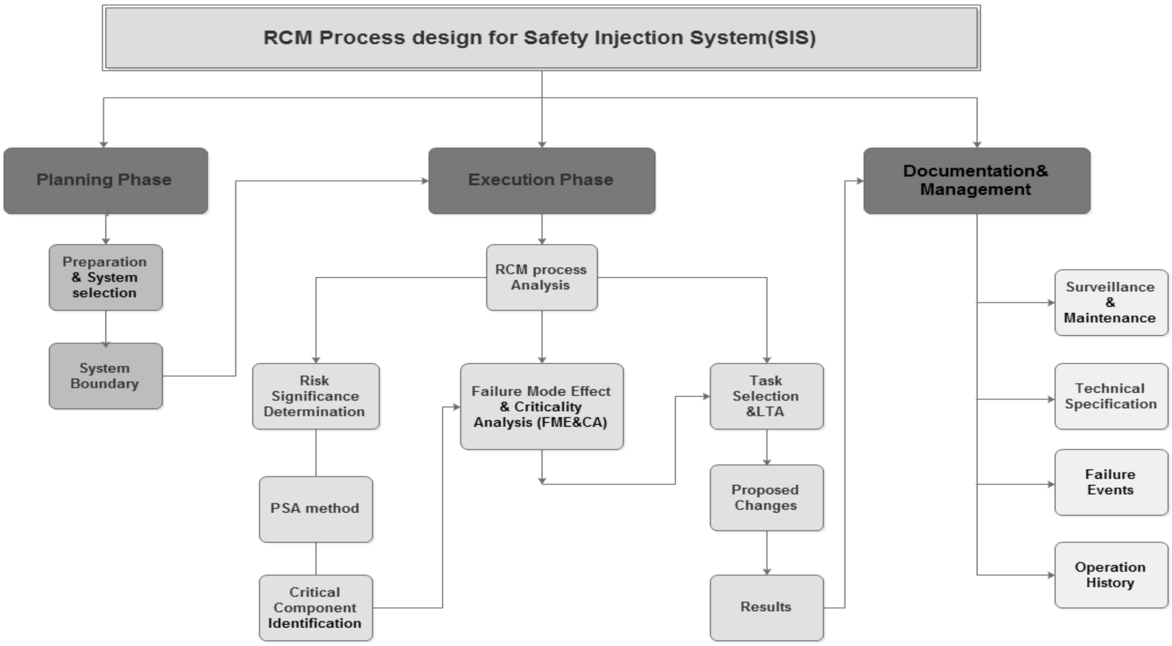
3.3.6 System Verification

In this step, after system design is developed based on the system requirements, assemble the system components into a working level and verify the requirements, the objectives of this step are:

- Integrate and verify the system in accordance with the high-level design requirements, verification plans and procedures
- Confirm that all interfaces have been correctly implemented
- Confirm that all requirements and constraints have been satisfied

3.3.7 System Validation

In this step, after the system has passed system verification and is installed in the



[Figure 3] RCM process steps

operational environment, a regional agency, or another entity, runs its own set of tests to make sure that the deployed system meets the original needs identified in the concept of operations. After that installed the system and trained the users, and the customer has successfully conducted acceptance tests and formally accepted the system. In systems engineering, we draw a distinction between verification and validation. Verification confirms that a product meets its specified requirements. Validation confirms that the product fulfills its intended use.

4. Applying RCM for SIS

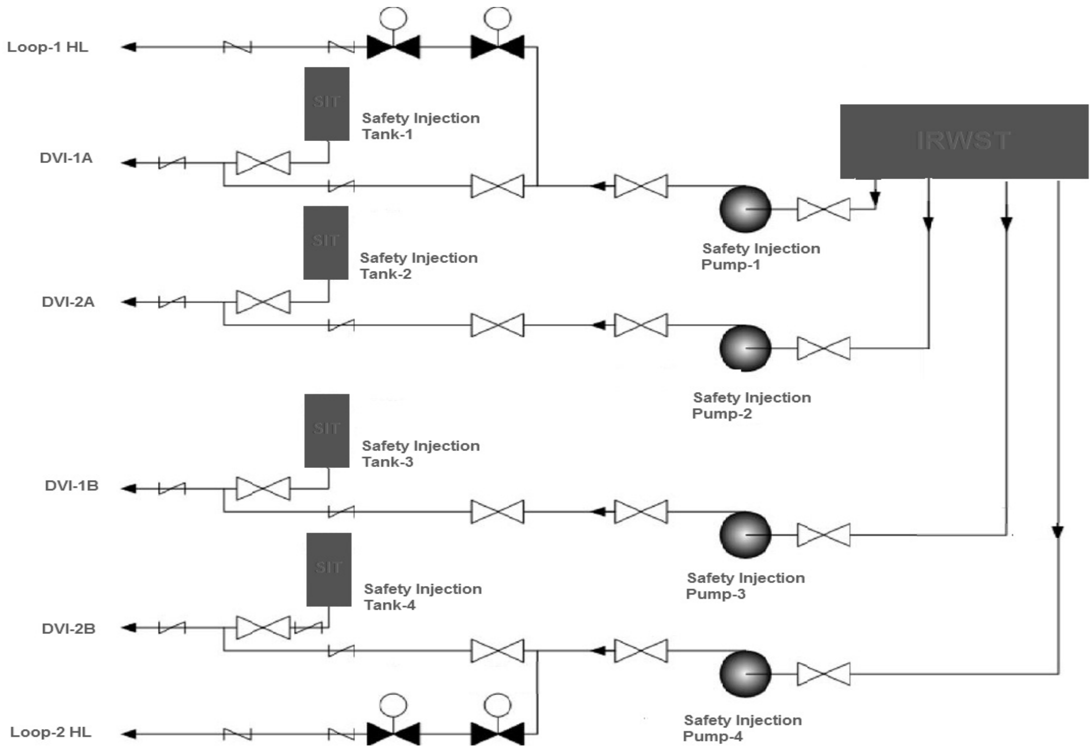
4.1 Function of Safety Injection System

- Injects borated water into the reactor vessel to assure adequate shutdown margin.
- Provides long-term post-accident cooling.
- Limits fuel damage to maintain coolable core geometry.
- Removes the energy generated in the core and maintains the core subcritical after LOCA.
- Provide inventory make up and boration for reactivity control during safe shutdown, prevent boron perception in RCS during a long -term mode of system operation.
- Provide feed flow for feed- and-bleed operation in conjunction with pressurizer Pilot Operated Safety Relieve Valve (POSRV) to remove core decay heat during total loss of feed water to the steam generator [3-4].

4.2 System boundary

Selection and scoping of SSCs for SIS is further broken down into the following components:

- Safety Injection pump (SIP),
- Motor Operated Valve (MOV),



[Figure 4] Safety Injection System boundary

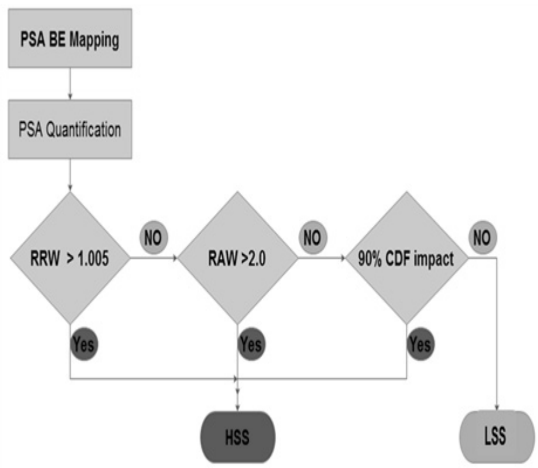
- Check Valve (CV) and,
- Safety Injection Tank (SIT).

4.3 Data collection

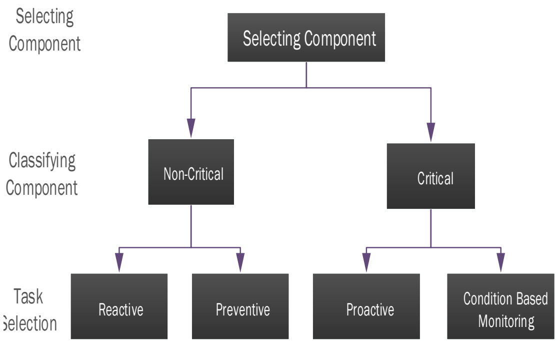
- Design specifications.
- Operating experience from the operations staff.
- Probabilistic Safety Assessment results from PSA experts.
- Review of INPO (Institute of Nuclear Power Operations) and EPRI (Electric Power Research Institute) documentation.
- Maintenance history from maintenance personnel.

4.4 Component importance determination

Using software (SAREX, KEPCO E&C) data to determine the safety significance of each component and identify the critical component. SAREX is the computer software that can conduct reliability analyses or probabilistic safety assessments of industrial facilities including nuclear power plants. Figure 5 shows the flowchart used to determine safety significance events and the critical component using the



[Figure 5] Safety significant determination flowchart



[Figure 6] Selection of Critical Component

following parameters:

- Risk Reduction Worth (RRW).
- Risk Achievement Worth (RAW).
- Core Damage Frequency Contribution (CDFC).

The data from SAREX software for RRW, RAW, and CDFC used to identify the High Safety Significance (HSS) events and Low Safety Significance (LSS) events [6-7].

4.5 Critical items selection

The objective of this step, to identify the analysis items that are potentially critical with respect to the function of the system identified. We should also identify items with high failure rate, high repair costs, low maintainability, long lead time for spare parts, or items requiring external maintenance personnel [8]. Safety injection pump, check valve, motor operator valve, and safety injection tank are selected as critical items.

Appendix (A) shows the highest risk significant component according to the PSA data.

4.6 Failure Mode Effect &Criticality Analysis (FME&CA)

Failure Mode Effect Analysis (FMEA) is a technique used to identify the potential functional failures and effects of those failures modes on component, system, and plant performance. The consequences of each failure mode determine the type of maintenance tasks applied to prevent any degradation that can lead to failure [9]. For each failure mode there may be several failure root causes.

The failure mode effect analysis for the critical component which has the highest risk significant based on the PSA output data shown in appendixes:

- Appendix (B) for SIP.
- Appendix (C) for MOV.
- Appendix (D) for CV.
- Appendix (E) for SIT.

<Table 1> Criticality classes

Category	Measure of Criticality	Criteria	Unit	Weight
E	4.0-3.0	Effect on Safety	S	50%
F	3.0-2.0	Effect on Availability	A	30%
G	2.0-1	Effect on Maintenance costs	C	20%

4.7 Criticality Analysis (CA)

The criticality analysis is based on the effects of the failure mode on the plant's safety, availability and maintenance cost. The class ranges from E to G in the criticality analysis table 1 shows the criticality class. Criticality analysis for each failure mode for the critical components in SIS shown in appendixes:

- Appendix (B) for SIP.
- Appendix (C) for MOV.
- Appendix (D) for CV.
- Appendix (E) for SIT.

4.8 Task Selection (LTA)

This is the stage of the RCM process that allocates maintenance tasks to various failure modes identified based on the criticality analysis using Logic Tree Analysis (LTA), the logic diagram considers five major criteria as follow:

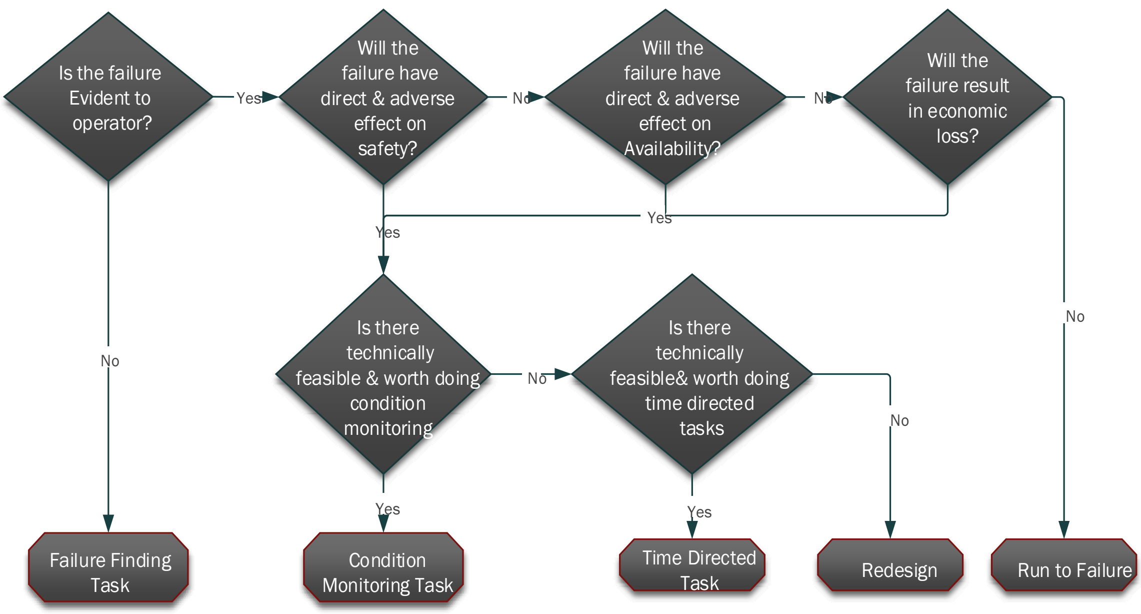
- Whether the failure is evident to the operator in the control room.
- Whether the failure has a direct effect on public or plant's safety.
- Whether the failure poses a threat to component availability.
- Whether the failure results in a major economic loss.
- Whether the maintenance task to be selected is technically feasible and worth doing.

The maintenance tasks available for con-sideration are:

- Failure finding tasks: whose failure modes are hidden and require functional tests to detect.
- Condition based tasks: tasks that monitor the degradation levels of failure modes.
- Time directed task: maintenance tasks performed periodically as scheduled.
- Re-design: where there is neither feasible condition directed nor time directed tasks applicable, and
- Run to failure: is applied on less safety and economical failure modes. Their failures are tolerable and corrective action is applied after failure.

Figure 7 shows the logic tree analysis flowchart which summarizes the process, and the output of this step is classified as:

- **Retain**: the new tasks exactly match the existing Preventive Maintenance (PM) tasks.
- **Modify**: the new tasks differ slightly in context or frequency from the existing PM tasks and will make these tasks more



[Figure 7] Logic Tree Analysis (LTA)

applicable and effective.

- **Delete:** the new tasks may be replaced by more applicable and effective tasks.
- **Add:** the new tasks intended to prevent or mitigate identified failures for the com-ponents whose existing tasks do not provide this appropriately. Add new tasks apply to all of those components for which there are no existing PM tasks but RCM has identified applicable and effective tasks.

The selected tasks for each failure root cause related to the critical component shown in appendixes:

- Appendix (B) for SIP.
- Appendix (C) for MOV.
- Appendix (D) for CV.
- Appendix (E) for SIT.

5. Improve SIP availability and reliability

Unavailability of SIP due to extension of Surveillance Test Interval (STI) calculated from equation (1) [10].

$$Q\,tm = \frac{[T1xF+T2]}{\text{Cycle time}} \qquad [1]$$

Where:

Qtm: SIP unavailability due to test and maintenance

T1: (Surveillance test+ Overhaul Test)

F: Testing frequency

Cycle time: Tow refueling periods

T2: Corrective maintenance time = (Downtime frequency x total cycle time x MTTR) = 8.42x10−5/hx36x30x24hsx20.9hrs =45.61hrs

Mean Time To Repair (MTTR) = 20.9 hours.

Based on the historical record of the SI pump operation and performance, the MTTR of the SI pumps in Ulchin power plant units is 20.9 hours [11]. Unavailability of the pump after extending the STI to six months will be (Qtm) = 0.0020679.

The reliability of SIP calculated from the equation (2) [12].

$$R\,(t) = 1 - Q\,tm \qquad [2]$$

Where:

R (t): Reliability of the pump

Qtm: Unavailability of the pump

R (t) = 1− 0.0020679 = 99.793

The reliability of safety injection pump will be 99.793 % in two refueling periods.

Condition based Maintenance increases the operational availability of the SIP because of the increasing in the Mean Time To Failure (MTTF), as availability calculated from the equation (3).

$$\text{Aavailability} = \text{MTTF} / (\text{MTTF} + \text{MTTR}) \qquad [3]$$

Where MTTR is the Mean Time To Repair.

Extending the surveillance test interval would lead to an improved pump's availability, eliminate unnecessary maintenance tasks, and optimize maintenance activities; the new surveillance test interval will be sex months.

6. Conclusions

RCM methodology is an effective approach to optimize the maintenance activities and increase the availability and reliability of the components and systems. According to PSA data SIP, MOV, CV and SIT, are the major components in the SIS. The FME&CA carried out in this study investigated the possible failure modes for the major components in the system. Application of RCM maintenance concluded that many of the current task types and task frequencies required revision in order to maintain the optimum levels of both availability and reliability of SIS. In several cases, specific components within the SIS will benefit from a shift in maintenance strategy from fixed interval to a CBM strategy. Such a strategy will ensure close monitoring of system and component performance without compromising nuclear safety or availability. It is recommended that the current SIS maintenance activities be reviewed and new PM tasks detailed in the tables adapted. After applying the RCM process 62.7% of the potential failures can be detected and prevented by CBM, 28.9% of failure can be detected and prevented by time based maintenance, 4.2% needs to redesign, 4.2% for failure finding and no run to fail for any failure modes. The number of CBM task increased this will reduce components failure rates, improve reliability and reduce run to fail components. For SIP which is the main component in the SIS and its unavailability has a great contribution to system unavailability, the surveillance test interval can be extended from three months to six months and this will lead to decrease pump unavailability and maintenance and test cost will reduced as well.

Acknowledgements

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<Appendix A> PSA Evaluation Results of SIS High Significant Components

Event	RAW		RRW		Failure probability		Significant
	RAW	RAW > 2.00	RRW	RRW > 1.005	Failure probability	90% CDF	
SICVWQ4V113/23/33/43	1.734E+03	Yes	1.024E+00	Yes	1.346E−05	No	High
SIMVWQ4616/26/36/46	1.221E+02	Yes	1.022E+00	Yes	1.781E−04	No	High
SISPP−S	1.593E+03	Yes	1.020E+00	Yes	1.250E−05	No	High
SIOPH−S−HLI	3.679E+01	Yes	1.010E+00	Yes	2.760E−04	No	High
SIMVWD2−321/331	3.679E+01	Yes	1.007E+00	Yes	2.044E−04	No	High
SIMPWQ4−CSP1A/B/SCP1A/B	1.505E+01	Yes	1.002E+00	No	1.138E−04	No	High
SIMVT1A−644	5.348E+00	Yes	1.001E+00	No	1.478E−04	No	High
SICVO1A−V245	5.348E+00	Yes	1.001E+00	No	1.170E−04	No	High
SICVO1B−V215	5.348E+00	Yes	1.001E+00	No	1.170E−04	No	High
SIMPKQ2PP02C/D	3.699E+01	Yes	1.000E+00	No	5.793E−06	No	High
SICVWQ3V540/41/43	5.226E+01	Yes	1.000E+00	No	2.855E−06	No	High
SIMPWQ2PP02A/B	3.686E+01	Yes	1.000E+00	No	3.680E−06	No	High
SICVWQ3V217/37/47	2.237E+01	Yes	1.000E+00	No	2.855E−06	No	High
SICVWQ2−V434/46	3.695E+01	Yes	1.000E+00	No	1.685E−06	No	High
SICVWQ4V215/25/35/45	5.348E+00	Yes	1.000E+00	No	1.346E−05	No	High
SICVWQ3−V424/26/48	4.279E+01	Yes	1.000E+00	No	1.127E−06	No	High
SIMPWQ3PP02A/B/D	4.278E+01	Yes	1.000E+00	No	1.067E−06	No	High
SICVWQ3V113/23/33	1.464E+01	Yes	1.000E+00	No	2.855E−06	No	High
SICVWQ4V568/569/1001/1002	1.494E+01	Yes	1.000E+00	No	2.621E−06	No	High
SICVWQ2−V424/26	3.682E+01	Yes	1.000E+00	No	9.980E−07	No	High
SICVWQ3V215/35/45	5.347E+00	Yes	1.000E+00	No	2.855E−06	No	High
SITKB1A−SIT01A	5.347E+00	Yes	1.000E+00	No	2.042E−06	No	High
SITKB1B−SIT01D	5.347E+00	Yes	1.000E+00	No	2.042E−06	No	High

<Appendix B> Safety Injection Pump (FME&CA and task selection) [12]

Item	Failure Root Cause	Effect on system	Criticality class	maintenance tasks (proposed)	Monitoring parameter
Bearing	Wear-fatigue-age	Loss of Redundancy	E	Condition directed [vibration analysis]	Bearing casing vibration
	Wear-fatigue-misalignment	Low system flow	E	Condition directed [vibration analysis+ Airborne acoustic analysis]	Pressure Vibration Noise level
	Wear-fatigue-excessive loading	Loss of Redundancy	E	Condition directed [vibration analysis]	Vibration Flow Measurement
	Wear-fatigue-personnel error	Loss of Redundancy	E	Failure Finding	Check Personnel training level
	Wear incorrect lubricant	Loss of Redundancy	E	Condition directed [Lubrication analysis]	Measure oil bearing quality
Seal	Worn out seals	Loss of Redundancy	E	Condition directed [Airborne acoustic analysis]	Pressure Flow
	Wear of rotor erosion	Loss of Redundancy	E	Condition directed [vibration analysis]	Measure loading+ vibration
	Cracked	Low system flow	E	Condition directed [Vibration analysis+ Airborne acoustics, operator rounds]	Measure vibration acoustics
Shaft	Cracked	Loss of Redundancy	E	Condition directed [Vibration analysis+ Airborne acoustics, operator rounds]	Measure vibration acoustics
	Shaft wear	Loss of Redundancy	E	Condition directed [Vibration analysis+ Airborne Acoustics]	Measure vibration acoustics
	Bend shaft	Loss of Redundancy	E	Condition directed [Vibration analysis+ Airborne acoustics, operator rounds]	Measure vibration acoustics
Impeller	Vane thinning	Low system flow	E	Condition directed [Vibration analysis]	Measure pump head
	Wear vortexing	Low system flow	E	Condition directed [Vibration analysis]	Measure impeller vibration
	Loose or failed key	Loss of Redundancy	E	Condition directed [Vibration analysis	Measure vibration acoustics
	Damage by debris	Loss of Redundancy	E	Re-design	install strainer
	Wear-cavitation	Low system flow	E	Condition directed [Vibration analysis]	Measure pump flow rate
	Face/shroud rubbing	Low system flow	E	Condition directed [Airborne acoustic analysis]	Measure impeller acoustic level
	Cracked Blade	Loss of Redundancy	E	Condition directed[Vibration analysis+ Airborne acoustics, operator rounds]	Measure flow and head

<Appendix B> Continued.

Item	Failure Root Cause	Effect on system	Criticality class	maintenance tasks (proposed)	Monitoring parameter
Motor Rotor	Loose lamination	Low system flow	E	Condition directed [Infrared−Thermography+ Motor current signature]	Measure winding temperature
	Failed rotor band/shorting rings	Loss of Redundancy	E	Condition directed [Infrared−thermography+motor current signature]	Measure circuit resistance
	Rotor/stator mechanical interface problem	Low system flow	E	Condition directed [Infrared−thermography+vibration analysis]	Measure vibration acoustics
	Loose retaining rings	Low system flow	E	Time directed [Scheduled restoration, general inspection, Replace rings]	Replace ring
	Loose rotor cage	Low system flow	E	Time directed [scheduled tightening, partial disassembly, Replace cages]	Replace cages
	Contaminated laminations	Low system flow	E	Failure Finding	Flow
	Winding insulation degradation	Loss of Redundancy	E	Time directed [insulation diagnosis, partial disassembly]	Measure winding temperature+ PI level
	Winding insulation degradation from corona	Loss of Redundancy	E	Time directed [insulation diagnosis, partial disassembly]	Measure winding temperature
	Loose blocking & bracing	Loss of Redundancy	E	Time directed [Partial disassembly, general inspection]	Appearance

<Appendix C> Motor Operated Valve (FME&CA and task selection)

Sub-component	Failure mode	Failure effect	Criticality Class	maintenance tasks (proposed)	Monitoring parameter
Stem	Stiffness of stem movement	Does not close	E	Condition directed [Infrared-Thermography + motor circuit analysis]	Monitoring of motor power and stem forces
		Does not close	E	Time directed [Scheduled inspection and functional test, partial disassembly, Scheduled cleaning and lubrication of stem]	Measure Stem Torque
		Does not close	E	Condition directed [vibration analysis]	Measurement of stem forces
		Does not close	E	Condition directed [Lubrication analysis]	Measure oil quality
	Breaking of stem nut	Does not close	E	Condition Monitoring [Infrared-Thermography + motor circuit analysis]	Monitoring of stem forces and motor power
		Does not close	E	Time directed [Scheduled inspection and functional test, partial disassembly, Replacement of stem]	Measurement of stem forces
Torque switch	Wrong adjustment/setting	Does not close	E	Time directed [Scheduled inspection and functional test, partial disassembly, Adjustment of torque switch]	Monitoring of torque switch tripping
	Wrong operation Torque switch	Does not close	E	Condition directed [Vibration analysis+ Airborne acoustics]	Measurement of stem force
		Does not close	E	Condition directed [vibration analysis]	Monitoring of limit switch tripping.
		Does not close	E	Redesign	Change location
Limit switch	Wrong setting	Does not close	E	Time directed [Scheduled inspection and functional test, partial disassembly]	measurement and monitoring of limit switch tripping
	Wear	Does not close	E	Condition directed [vibration analysis+ Airborne acoustic analysis]	Measure loading+ vibration
	Human factors	Does not close	E	Failure finding	Check personnel training level
Micro switch	Stiffness of mechanism	Does not open	E	Time directed [Scheduled inspection and functional test, partial disassembly]	The measurement and monitoring of motor power
	Dirtiness of contacts	Does not open	E	Condition directed [Scheduled cleaning, partial disassembly]	Measurement of stem forces
Hand drive	Breaking of declutch lever key	Does not open	E	Redesign	Change declutch lever key location
Contactors	Dirtiness and oxidation of contacts	Does not open	E	Time directed [Scheduled servicing, partial disassembly of contactors]	Measure temperature of connections
		Does not open	E	Condition directed [Infrared-thermography]	Measure circuit resistance
Contactors	Dirtiness and oxidation of contacts	Does not open	E	Time directed [Scheduled servicing, partial disassembly of contactors]	Measure temperature of connections
		Does not open	E	Condition directed [Infrared-thermography]	Measure circuit resistance
Circuit board for contactor relays	Electric component fault	Does not open	E	Time directed [Scheduled inspection and functional test, partial disassembly]	Measure temperature of connections
		Does not open	E	Condition directed [Infrared-thermography]	Replacement if necessary

<Appendix D> Check Valve (FME&CA and task selection)

Sub-component	Failure mode	Failure Effect	Criticality Class	Proposed Maintenance Task (proposed)	Monitoring Parameters
Hanger pin	Hanger pin wear	Does not open	E	Condition directed [Radiography]	Dimensions, Appearance and Roughness
	Corrosion	Does not open	E	Time Directed [Scheduled inspection and functional test, lubrication Disassembly]	Dimensions, Appearance and Roughness
	Fracture	Does not open	E	Time Directed Disassembly Replacement]	Dimensions, Appearance and Roughness
	Hanger Pin bearing	Does not close	E	Time Directed [Scheduled inspection and functional test, lubrication disassembly]	Dimensions, Appearance and Roughness
	Wear	Does not close	E	Condition directed [Radiography]	Dimensions, Appearance and Roughness
Seals	External Leakage	Loss of Function	E	Time Directed [Scheduled inspection and Replacement]	Appearance, Packing gland fitting
Oburator	Wear	Loss of Function	E	Condition directed [Eddy Current Magnetics]	Dimensions Cracking, Obturator-movement,
	Corrosion	Loss of Function	E	Time Directed [Scheduled inspection and Replacement]	Appearance Roughness Force or Torque
Hanger	Wear	Loss of Function	E	Condition directed [Radiography]	Dimensions, Appearance
	Corrosion	Loss of Function	E	Time Directed [Scheduled inspection and Replacement]	Appearance, Roughness Force or Torque
	Fracture	Loss of Function	E	Time Directed [Scheduled inspection and Replacement and functional test, disassembly, replace]	Appearance Roughness Cracking
Spiral wound Gasket	Leaking	Loss of Function	E	Condition directed[Leak monitoring]	Appearance, Noise, packing gland fitting
Cap	Wear	Loss of Function	E	Condition directed [Leak monitoring]	Appearance, Dimension
Seat	Wear	Loss of Function	E	Condition Monitoring [Back Flow Test Ultrasonic Testing]	Dimensions Appearance Roughness
	Corrosion	External leakage	F	Time Directed [Scheduled inspection and Replacement]	Appearance, Roughness, Force or Torque
	Foreign Materials	External leakage	F	Condition directed [Acoustics, eddy Current]	Appearance

<Appendix E> Safety Injection Tank (FME&CA and task selection) [3]

Item	Failure Mechanism	Root Cause	Effect on system	Criticality Class	Maintenance task (proposed)	Monitoring parameter
SIT Discharge Isolation Valves	Fails to Open	Elect. malfunction , mech. binding, contamination	No impact on performance of safety function	F	Condition directed [vibration analysis+ Airborne acoustic analysis]	Valve position indicator
	Fails to close	Elect. Malfunction, mech. binding, operator. error	Loss of flow from one SIT	E	Condition directed [Infrared Thermography + motor circuit analysis]	Valve position indicator; Periodic testing
SIT Fill and Drain Isolation (Valves designed to fail closed and is normally closed)	Fails Open or fails To close on SIAS	Elect. Malfunction, seat failure, contamination	None	F	Condition directed [vibration analysis+ Airborne acoustic analysis]	Valve position indicator
	Fails closed	Airline separated from operator; mech. binding	No impact on performance of safety function	E	Condition directed [vibration analysis+ Airborne acoustic analysis]	Valve position indicator; SI tank level
SIT Fill Line Isolation Valve normally closed and is designed to fail closed	Fails open Or fails To close On SIAS	Elect. malfunction, seat failure, contamination	None	F	Condition directed [vibration analysis+ Airborne acoustic analysis]	Valve position indicator
	Fails closed	Mech. binding, airline separates from operator	No impact on performance of safety function	F	Condition directed [vibration analysis+ Airborne acoustic analysis]	Valve position indicator; SI tank level indicator
Nitrogen Supply Valves (Valve is designed fail closed)	Fails closed	Mech. binding, airline separated from operator.	Cannot repressurize one SI tank when required	E	Condition directed [Vibration analysis, system engineer walk down]	Valve position indicator.
	Fails open	Mech. binding, seat erosion, Elect. Malfunction.	None	F	Condition directed [InfraredThermography+ Motor current signature]	Valve position indicator
SIT Wide range Level indication Narrow(Provide high and low level alarms)	Fails to indicate correctly	Elect. Malfunction, mech. failure	Inconsistent level indication between SIT level indicators	F	Condition directed [Vibration analysis, system engineer walk down]	Level indicators in control room
SIT Wide Range Pressure Indicator(Provide high and low level alarms)	Fails To indicate correctly	Elect. malfunction	Inconsistent level indication between SIT level indicators	F	Condition directed [Vibration analysis, system engineer walk down]	Pressure indicators in control room