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Selection of Architect Engineering Concept for Barge Mounted SMR Using Systems Engineering Approach

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Abstract : The trade-off studies in the concept development stage to assess the relative goodness of alternative systems concepts for AE (architect engineering) design for the Barge Mounted SMR (BMSMR) is introduced. With respect to design margin, system performance, schedule and risk, the design selection is cond ucted using the following characteristics; barge mobility, system safety under the natural disaster (seismic), power output, interfacing with the other system, and the additional supporting functions as desalination. There are three findings that should be remedied; deficiencies in the assumed characteristics of the system being modeled, deficiencies in the test model, and excessively stringent system requirements. This study is performed using systems engineering approach with trade off matrix method. In order to execute this work, concept development stage is divided into three (3) phases as NA (needs analysis), CE (concept exploration), and CD (concept definition).

Key Words : Architect engineering, Need analysis, Concept exploration, Concept definition, Barge Mounted SMR, Trade off matrix method

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1. Introduction

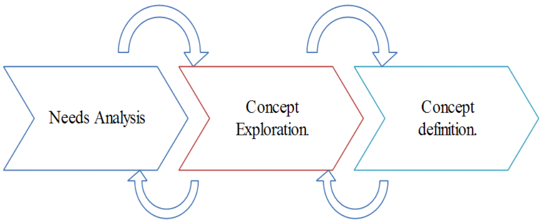
Selection of Architect Engineering is a very important process in planning and implementation of nuclear power plant. Small reactors are reactors with an equivalent electric power of less than 300 MW (e) and medium sized reactors are reactors with an equivalent electric power of between 300 and 700 MW(e) [4]. Barge mounted SMR (BM-SMR) is a floating small reactors with an equivalent electric power output of less than 300 MW(e). Barge mounted SMRs are affordable nuclear power option for developing countries with limited investment capability. BM allows for generation of power for small electrical grids and powering desalination systems for developing nations which have lot of power scarcity. The selection of architect design ensures; system' s safety under natural disaster, integrity of structures to deliver output power within 300MWe, integrating with other systems and supporting functions.

This paper presents the selection of optimum BMSMR alternative from different possible candidates engineering architectures. The initial concept development of architect engineering of a BMSMR is accomplished in a safe and secure way considering the alternatives available and provides sustainable structures of internal, external and common mode phenomena by optimizing the functions of BMSMR. Additionally it presents the concept development phases and steps using systems engineering approach.

The work development uses a common project file structure for the capture of project design products. This system is a network-accessible data repository which is maintained on a project server accessible by all members. This system is called the Integrated Database Management System (IDMS). Data produced by the systems engineering tasks, including all documentation, plans, models, studies, reports, system design review results, views, and rationale, are stored in the IDMS. The project adopted a needs driven approach, where the needs of the customer are analyzed and various options to solve the needs are explored. The best architectural concept is then selected based on provided criteria. The systems engineering approach includes both technical and management processes in a timely manner which is necessary to make a critical decision among the alternatives [1].

2. Methodology

The concept development process is important in developing new systems or making improvement on the existing systems. The concept development process consists of the (1) Needs analysis (2) Concept Exploration (3) Concept definition [2]. These three stages are interconnected in concept development stages. This process is shown in figure1.



[Figure 1] Concept development process

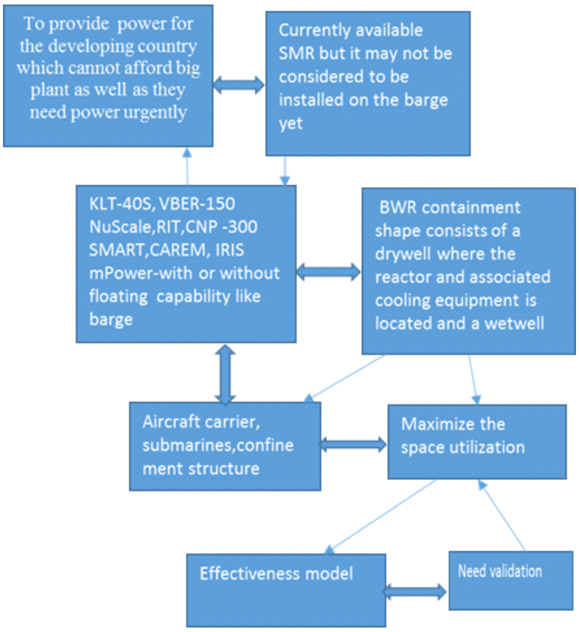
The trade- off matrix method is used to come up with best alternative solution to make a choice of BMSMR.

2.1 Needs analysis

The needs analysis is a phase that is responsible for the determination of the need or desire for a new system. Small modular reactor (SMRs) has become the only affordable nuclear power option for many developing countries in the world with limited investment capability [5]. The SMRs allows for incremental construction which reduces significantly the capital at risk compared to large conventional nuclear power plants [7].The aim of SMRs is to achieve enhanced safety and improved economics. To enhance safety and reliability, the design organization has incorporated inherent safety features and reliable passive safety systems. The Initiation of a new system development generally comes from operational deficiencies [1].The perception of a serious deficiency in a current system designed to meet an important operational need. There is need to utilize the SMR for villages and towns in off-grid locations, industrial installations in off-grid locations, sea water desalination and enhance the plant’s availability.

In Boiling Water Reactor, the steam going to the turbine that powers the electrical generator is produced in the reactor core rather than in steam generators or heat exchangers. BWR containments are pressure suppression pool type, and the steam discharged into the containment is led to the water pool of the pressure suppression chamber, cooled and condensed, and the pressure rise within the containment is suppressed as a result. Moreover, as the temperature and pressure of the containment rise due to the fuel decay heat in a long term after an accident, it is necessary to cool the inside of the containment and it is also necessary to remove radioactive materials such as iodine within the containment. For such purposes, the containment spray system is provided within the containment (drywell spray, pressure suppression chamber spray). Furthermore, the standby gas treatment system is provided in the reactor building so that the radioactive materials will not be released to the outside of the containment. In addition, following a loss of coolant accident, the temperature of fuel cladding could rise and hydrogen could be generated by a water-metal reaction, which could impair the containment integrity due to hydrogen gas combustion. In order to prevent such a case, BWR containments are kept inert with nitrogen gas during normal operation, and the flammability control system to prevent hydrogen combustion by recombining the generated hydrogen gas with oxygen gas [11].

In this study, this is done using Integrated Definition Function model IDEF0 to show the



[Figure 2] Need Analysis of BMSMR

activities involved in the needs analysis phase.

In the SE process, Need analyses are divided into 4 stages and these stages are shown for this study in the following figure 2.

2.1.1 Operational Requirements

This is the first stage of needs analysis and involves elicitation of customer' s requirements. These refer largely to the mission and purpose of the system. The mission of this works is to select A/E concept in the view point of developing country, Moreover, it has two different purposes such as: optimize the BMSMR design, and how to apply it apply into the real work.

Needs are the capabilities a stakeholder consider necessary to achieve objectives while requirement is a condition or capability needed by a stakeholder to solve a problem or achieve an objective. Requirements are subset of needs. Table 1 shows the overall operational requirements of the systems.

<Table 1> SMR Operational requirements

Operational requirements	Characteristics
design margin	power output
system performance	Mobility ,desalination
Schedule & risk	system safety under the natural disaster
Design selection	interfacing with the other system

2.1.2 Functional Analysis

This stage of needs analysis extracts the functions from the stated operational objectives. Table 2 shows functional requirements for SMR architecture.

<Table 2> SMR Functional requirements

Requirements	Functions
Reduce the radiation of the neighborhood	To shield or shelter the radiation
Provide mobility of the barge	To serve various part of the sea side area
Provide the safety from the earthquake	To make earthquake proof system
Provide larger desalination	To increase capacity of the desalination tank

2.1.3 Allocating functions to subsystems

Once the functions have been identified, they are allocated to the subsystem as illustrated in the table 3.

<Table 3> Functional allocation of sub-system

Functions	Sub-functions
To notify the radiation dose rate	For the density of radiation displaying system on the containment building
To make earthquake proof system	To make SSE greater than 0.3g for anchor & foundation intensity
To make wave power	Wave power can be used for power as well as protecting the foundation of the barge
To increase desalination tank capacity	Desalination 50,000 ton/day

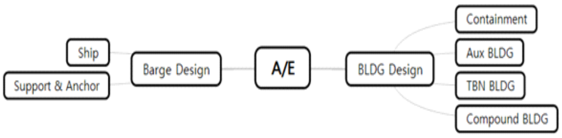
2.1.4 Feasibility definition

The feasibility is evaluated in terms of cost effectiveness. The output of this process is a more refined operational objective.

Defining a feasible concept in terms of capability and estimated cost by varying (trading off) the implementation approach are required. Sub-functions & Physical requirements are considered in this stage. Table 4 shows the feasibility definition for the BM SMR.

<Table 4> Physical Visualization of BM SMR

No.	Sub−functions & Physical requirement
1	Wall thickness 1.5m
2	Dome thickness 1.3m
3	Pre−stressed concrete shell with steel liner
4	Displaying to the system the density of radiation on the containment building.
5	A holder for display system on the wall which supports the display.
6	To make SSE greater than 0.3g
7	Anchor & foundation intensity Heavy anchor support the SMR and protect against typhoon & storm surge.
8	Desalination Tank 50,000 ton/day



[Figure 3] Schematic arrangement for BM SMR

2.1.5 Need validation

This stage ensures viability of stated requirements and a sustainability of architectural design on the basis of Operational Analysis, cost, functional analysis and feasibility definition of the KINGS Barge Mount SMR conceptual architectural design and construction. Schematic arrangement with different subsystems of BM SMR is shown in figure 2.

2.2 Concept Exploration

This is the second phase of concept development which focuses on the operational analysis for the BMSMR. It basically involves the operational requirements from the needs analysis phase and looking at the predecessor systems earlier designed. Most of SMRs are supposed to build inland and they lack mobility except Russian KLT type reactors which are used for ice breakers and there is ongoing project to use this kind of reactor that is mounted on a ship for electricity generation in icy lands of Russia that are far away from grid. On the other hand, one of the important issues should be dealt with after deciding reactor type is to modify and construct this reactor on a barge. Four stages of concept exploration are described hereunder.

2.2.1 Operational requirements analysis

The output of needs analysis phase (operational requirements) forms the input to this stage. Table 5 shows a set of refined operational objectives.

<Table 5> Operational requirements analysis

Operational Requirement	Analysis
Fast mobility of the barge	Mobility→ basic functions of barge As fast as 5km/h
To intensify the safety in terms of manmade and natural disaster	Safety → defining disasters(earthquake, flood, tsunami, tidal wave−aircraft crash) The barge should provide physical protection
To improve the capability of cleaning & circulating the air in the containment vessel	Safety & Efficiency(capacity of circulation system, then the redundant system for circulation in case of emergency)
To have a larger & purer desalination capability	Redundant desalination tank

2.2.2 Formulation of performance requirement

This formulation is concerned with what to be performed and by how much to perform the functions in order to meet or satisfy the operational requirements. In attempting to satisfy the operational requirement, many options can be proposed from which the best alternative should be chosen

The performance requirements are formulated as follows:

-The barge shall be able to move at 5km/h

-The system shall maintain a seismic condition of greater than 0.3 g.

-The desalination tank shall have the capacity of 50,000ton/day.

-The containment shall prevent release of radiation dose of 0.1% of during normal operation and 5% during DBA.

-The containment shall have a wall thickness of 1.5m, dome thickness of 1.3m at 0.2%/24h leak rate.

2.2.3 Derivation of subsystem functions and elements

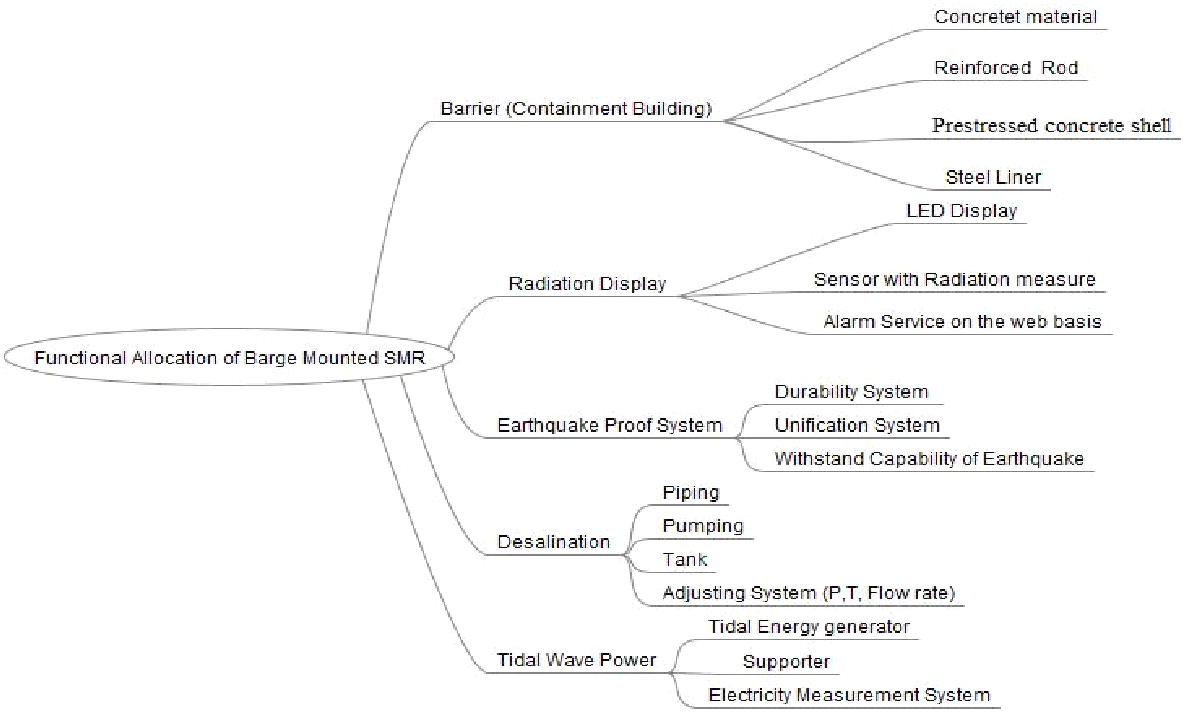
The elements allocated to the functions are analyzed for each function as shown in the table 6.

<Table 6> Derivation of functional elements

Functions	Functional Elements
To shield or shelter the radiation	Barrier (containment building)-Concrete material, Reinforcing rod, Pre-stressed concrete shell with steel liner
To notify the people about density of radiation.	Display (LED),Sensor which measures radiation, Alarm service on web basis
Earthquake proof system.	Devices which sense the earthquake measure the magnitude and calculate the effect to the system.
Increased capacity of the desalination tank	Pump, Piping, Tank, Adjusting system(pressure & flow)

2.2.4 Functional Allocation

The functional allocation for the architect engineering for the barge mounted SMR is il-



[Figure 4] Functional allocation

lustrated in figure 4.

The list of functional inputs, transformational functions and the outputs for the five performance requirements is illustrated in the tables 7, 8, 9, 10, 11.

<Table 7> Barrier (containment building)

Sea water	Converting salt water into fresh water	Fresh water
Impurities (fish, shell)	Boiling & Osmosis	Filtered impurities

Table 7 is used to show the input to the containment and its capability to prevent the release of radioactive material to the environment. This is verified by the output of the transformation process.

<Table 8> Radiation Display

Input Function	Transformative Functions	Output Functions
Radiation	Calculating it as number	Display the number
	Sensing the radiation	Show the current status

Table 8 illustrates the functions of the radiation display and how it uses the input function and transforms it into output numerical display.

<Table 9> Earthquake condition

Input Function	Transformative Functions	Output Functions
Earthquake	Heat	Endure the strength
Other shocks	Shaking, Cracking	Barge Safety

Table 9 shows response to seismic condition and the response signal.

<Table 10 > Wave Power

Input Function	Transformative Functions	Output Functions
The wave force	Converting wave into electricity	Electricity
Sea wave	Collecting the wave energy	Show the amount of electricity

<Table 11> Desalination

Input Function	Transformative Functions	Output Functions
Radiation	Corrosion	Isolation & quarantine
High Pressure	Absorbing	Safety

Table 11 illustrates the desalination process and the output of fresh water is processed from raw sea water

2.2.5 Operational Concept (CONOPS)

The architectural project includes all planning, execution, implementation, and training for a new model of structure. In order to effectively carry out the project it is important to ensure adequate resources for designing, building, testing, and implementing the new structure. Containment Building should prevent the leakage of radiation. The containment is the fourth and final barrier to radioactive release while the first being the fuel ceramic itself, the second being the metal fuel cladding tubes, the third being the reactor vessel and coolant system [6]. Since BMSMR is situated in the remote area where living population is not available surrounded 10 km or more area, reactor vessel can be surrounded in a containment structure equipped with a light bulb containment design in a steel shell and concrete containment design. In the design and layout of containment systems, sufficient space and shielding should be provided to ensure that maintenance and operations can be carried out without causing undue radiation exposure of personnel [9]. Power generated module should be mobile module and additional module should be provided to protect mobile module. Auxiliary building, radioactive waste management facilities, desalination facilities and other necessary facilities should be designed and constructed.

2.2.6 Implementation of concept Exploration

This stage of concept exploration looks at the various alternatives candidates available in the market in terms of their performance capabilities. Table 12 shows the evaluation of the SMRs architecture engineering from various countries while table 13 shows refined SMR alternatives with the requisite performance requirements from which trade off analysis is carried out.

Table 10 shows the conversion of sea wave into electricity.

<Table 12> SMR alternative A/E designs

No	SMR	Country of origin	Mobility (Km/h)	Seismic	Output Power (MWe)	Desalination capacity(ton/day)	Area(m^2)	Cost (USD/ KWe)
1	KLT-40S	Russian Federation	Yes	0.3g	35	Yes	4200	-
2	VBER-150	Russian Federation	Yes	0.25g	110	Yes	1785	-
3	NuScale	USA	No	0.15g	45	Yes	880	-
4	CNP-300	China	Yes	0.25g	325	Yes	6750	-
5	CAREM	Argentina	No	NA	25	NA	-	-
6	IRIS	International Consortium	No	0.25g	335	NA	6750	-
7	mPower	USA	No	NA	180	NA	-	-
8	RIT	Russian Federation	Yes	0.25g	150 MWth	100000	8250	-
9	SMART	Republic of Korea	No	>0.18g	100	40000	-	-

The nine candidate solutions are reduced to six as shown in table 13 based on the desalination screening criterion. The candidate solutions without desalination capability are screened out and CAREM, IRIS, and mPower are eliminated as shown in table 13.

<Table 13> Refined SMR candidate alternatives

No	SMR	Country of origin	Mobility (Km/h)	Seismic	Output power (MWe)	Desalination capacity(ton/day)	Area(m^2)	Cost (USD/KWe)
1	KLT-40S	Russian Federation	Yes	0.3g	35	Yes	4200	-
2	VBER-150	Russian Federation	Yes	0.25g	110	Yes	1785	-
3	Nuscale	USA	No	0.15g	45	Yes	880	-
4	RIT	Russian Federation	Yes	0.25g	150 MWth	100000	8250	-
5	CNP-300	China	Yes	0.25g	325	Yes	6750	-
6	SMART	Republic of Korea	No	>0.18g	100	40000	-	-

2.2.7 Performance requirements validation

This is performed by integrating the requirements derived from the alternative candidate solutions and their effectiveness to meet the stated operational requirements

This is the final stage of concept exploration phase. The performance requirements are validated against the user' s needs, consistency with the requirements and clarity as shown in the table 14.

<Table 14> Performance requirement validation

Operational objective	Traceability To user' s needs	Consistency With requirements	Clarity
Mobility- as fast as 5km/h	Yes	Yes	Yes
Safety	Yes	Yes	Yes
Desalination tank capacity	Yes	Yes	Yes
Seismic Condition	Yes	Yes	Yes

2.3 Concept Definition

This phase marks the beginning of serious work of defining the functional and physical characteristics [2]. The selected alternative is supposed to meet all the refined operational needs as described in the preceding conceptual phases.

This is the final phase of concept development process where the best solution candidate is selected.

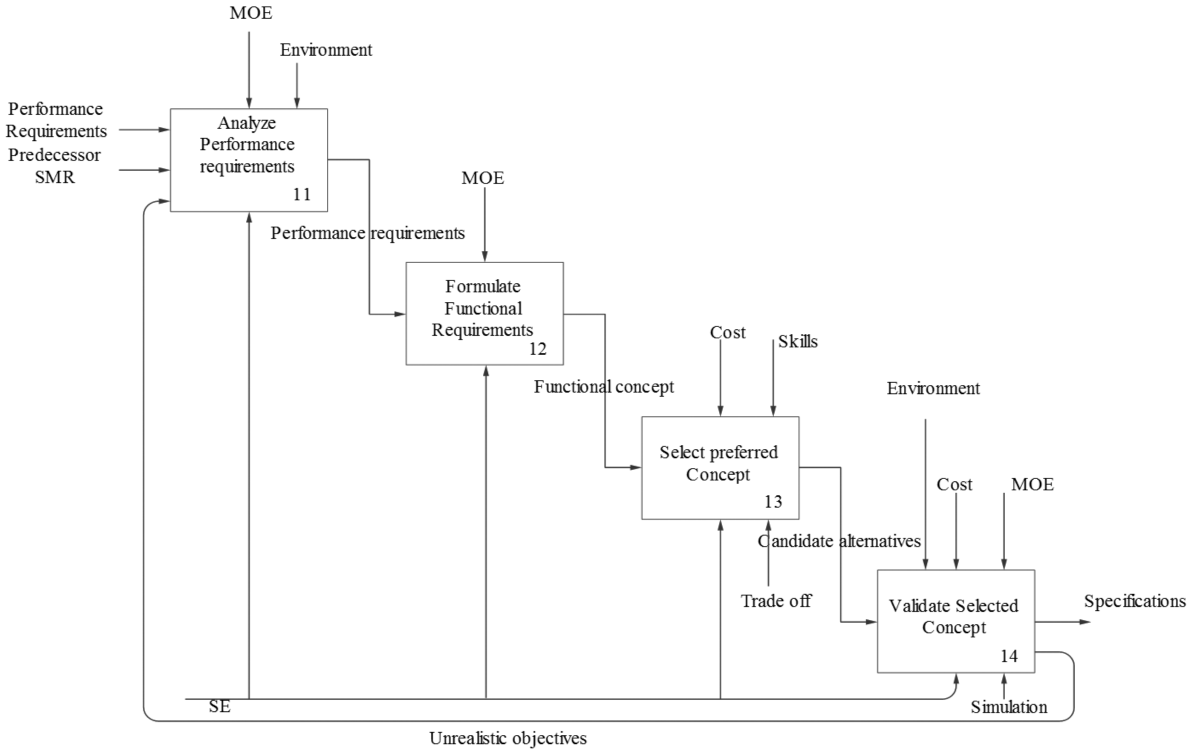
In this phase trade off analysis is carried out to determine the optimal solution. The input to this phase is the set of output of concept exploration phase (validated performance requirements). This phase has four stages modeled using IDEF0 level 1 shown in figure 4 [8]. An IDEF0 model represents the functions, decisions, processes, and activities of a system which is particularly useful for representing complex systems [3].

In this phase, candidate SMR alternatives are evaluated by using trade-off analysis method. In order to implement such a method values should be assigned to each measure. To determine those values engineering judgment is used.

In concept definition, selection is based on the program risks that could result from a number of sources namely:

(1) Un-proven technology
(2) Difficulty in performance requirements
(3) Severe environment
(4) In-adequate funding or staffing and
(5) Un-duly short schedule

These factors are used as controls and enabling mechanisms at each stage of concept definition phase. The predecessor SMR is used as a guiding concept for selection of the suitable BMSMR solution for this work.



[Figure 5] IDEF0 Level 1 for concept definition

Figure 5 shows how each stage is analyzed using inputs, controls, mechanisms and the output of each stage becomes the input to next stage for BMSMR.

2.3.1 Performance Requirement analysis

The analysis addresses reliability, maintainability, and support facilities, as well as environmental compatibility for the BM SMR.

2.3.1.1 Compatibility Requirements

The compatibility of the barge mounted system considered the following factors:

- Barge mobility: New barge should be made considering the weight of the NPP since the facility would have additional power source such as wave power system.

- Safety system (seismic condition): The system should be stable during earthquake conditions. The anchor which fixes the barge to the ground level should have enough length, strength and durable and there should be direct communication with the seismic sensors.

- Desalination system: The water treatment system should be separated from coolant system and endure corrosion arising from sea water regardless of salinity and temperature.

2.3.1.2 Reliability, Availability and Maintainability requirements(RAM)

The RAM of the system is important so that at the early stage of the life cycle, the reliability issues are fulfilled. The requirements for maintenance of the system should be addressed and all support facilities required determined. The fulfillment of the RAM criteria shall be achieved as follows;

- Barge: Reliability shall be achieved by ensuring that the barge supports the structures effectively without stress even in the event of natural disaster. Maintainability of the barge shall be done in accordance with the overhaul period of the SMR. In order to achieve availability, the barge shall ensure SMR operation in the event of internal or external shock.

- Desalination system: In order to ensure the reliability of the desalination system, reliability should be achieved on the purity of the drinking water and the level of salinity on the processed water. The maintenance of the desalination plant shall be carried out in line with the planned overhaul of the SMR to avoid interrupting the plant' s operation. Availability of the system should be ensured through unclogged intake system, and vaporization facilities.

3.1.3 Environmental requirements

Environment impact assessment is very important in the execution of any project. In this regard, the system of interest should ensure the integrity of the containment to avoid any release of radioactive materials to the sea. The intake system should be well designed to sieve jelly fish and to protect any other marine life.

2.3.1.4 System Life Cycle Scenario

In order to understand the situations that the BM SMR system will encounter during its lifetime, the following scenarios shall be adhered to;

a) Storage of the system and/or its components

The integrity of fuel storage system, auxiliary building, containment building should be monitored and maintained. These buildings are exposed to severe internal and external environmental condition.

b) Transportation

Transportation of the system to its operational site-Construction material could be shipped by boat or truck. In this case, used block should be changed without exposure to radiation during operation.

c) Assembly of system

Assembly and advance preparation of the system for operation should be done. Building the system using earthquake proof materials is advisable before commission. Variety of tests (such as nondestructive test) should be done on the structures (building).

d) Operation of the system

During normal operation, some mishaps may occur that might eventually develop into severe problems. In view of this a system monitoring program should be installed to track all operational parameters.

e) Routine Maintenance

Routine maintenance should be implemented every overhaul period. In case of emergency breakdowns, corrective actions should be taken and completed within the allowable outage time specified in the technical specification.

f) System modification and upgrading

To prevent early obsolescence, a system that uses high technology must be capable of periodic upgrading or modernization. In accordance with high edge technology, reinforced concrete shall be adopted to improve the integrity of the system.

g) System disposition

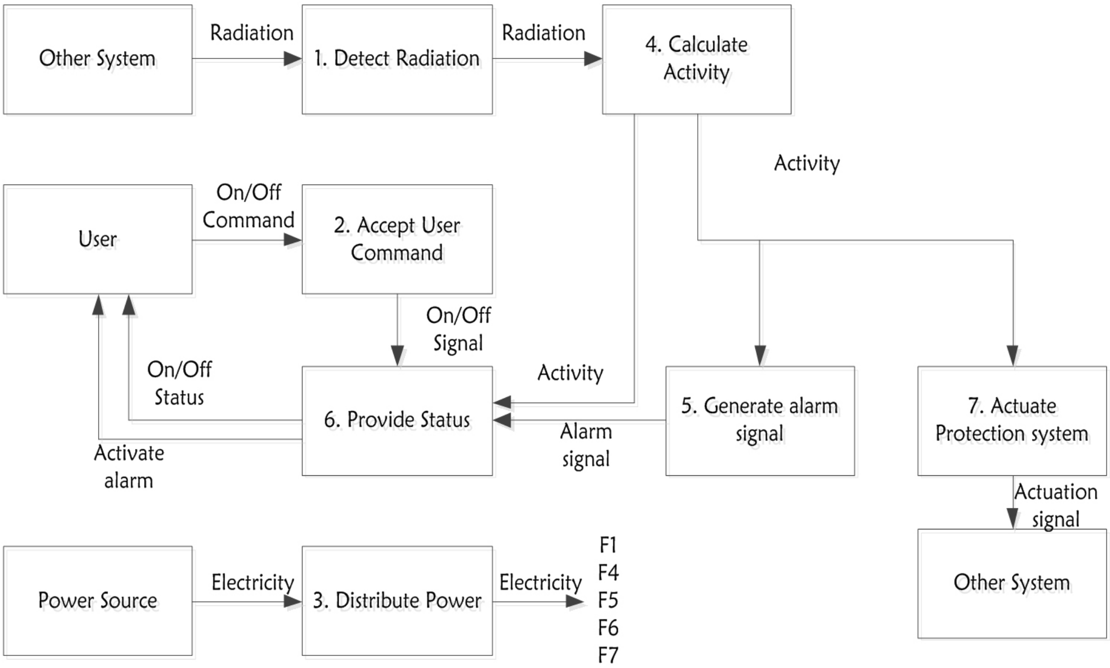
After 30~40 year of commercial operation, life extension shall be sought in line with the safety requirements of the plant’ s systems, structures, and component. Integrity tests shall be carried out on the system and the condition of the components evaluated to ascertain their safety conditions. Spent fuel and low intermediate level of the radio waste shall be transported to the repository. This whole system remodeling is worth considering because of its mobility

h) Auxiliary use.

The system shall be used as another source of generation facilities. (Solar, wind, tidal), There should be off limited section for the safety with warning signal.

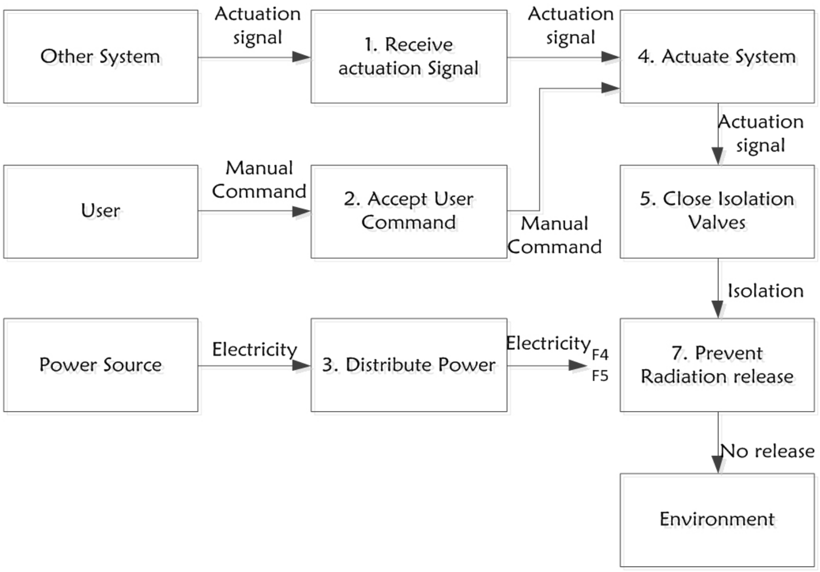
2.3.2 Functional analysis and formulation

In order to analyze function of the BM SMR, functional building blocks are used to illustrate the modularization and interface of elements to achieve the output. At this stage performance requirements are transformed into system functions as shown in the figures 6, 7 & 8.



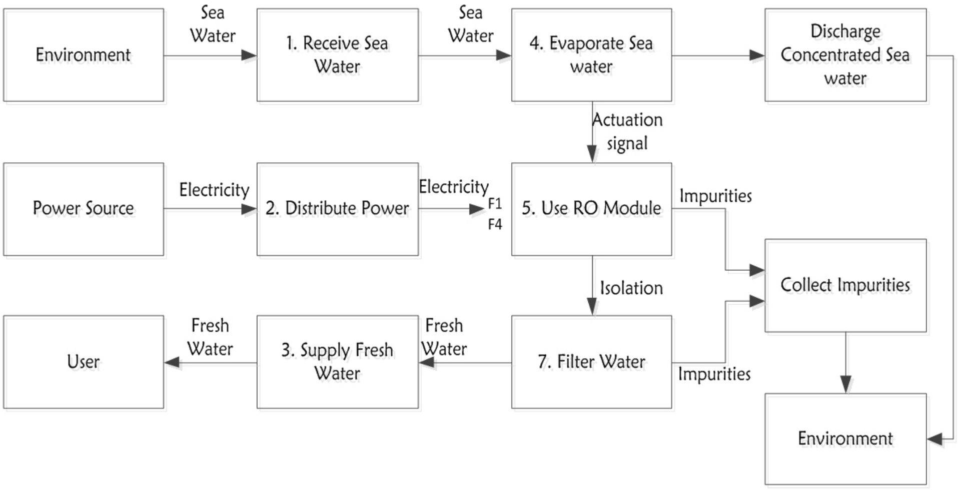
[Figure 6] Radiation Protection System

Figure 6 shows the radiation monitoring system architectural arrangement in terms of functional block diagram. The radiation emanating from the SMR is detected through radiation system and the output of this process used to calculate the level of radiation so that the radiation protection system can be actuated



[Figure 7] Containment Isolation System

Figure 7 shows the general arrangement of the containment isolation system. The modules receive signal of loss of coolant containment isolation, system is actuated to protect the containment integrity and prevent release of radioactive materials to the environment.



[Figure 8] Desalination System

Figure 8 shows the functional block diagram for the desalination system alongside power distribution. The sea water is received from the environment and evaporated through the evaporator and reverse osmosis (RO) module. The evaporated water then undergoes filtration in order to remove any impurities and the end product is fresh water

2.3.3 Trade Off analysis- Select Concept

In order to select the best BM SMR candidate solution for the listed requirements, trade off analysis is done on the available SMR alternatives. The trade- off analysis is used to come up with best alternative solution for the user to make a choice [10].

The tradeoff matrix compares the rating of six candidates conceptual SMRs with respect to five evaluation criteria:

Mobility- measured in Km/h

Seismic condition- measured in g

Power output- measured in kWe

Desalination tank capacity- measured in Ton/day

Cost- measured in USD/kWe

2.3.3.1 Weight allocation and Scoring Weight allocation

On a scale of 0-5, the maximum of 5 was assigned to seismic withstand condition due to its critical to safety. The next highest 4 was allocated to power output since it has a direct impact on the plant area required. Mobility was assigned 3 because it is not very critical but required for transportation. Desalination tank capacity was assigned value 2 because it is an auxiliary requirement for the system.

It is worth noting that the cost was not considered in the criteria since the exact cost of each SMR could not be found and it is excluded from the final weighted score.

Scoring

Based on the design values (mobility, seismic, output, desalination and area) for each alternative as shown in table 13, the score is allocated to each alternative from 1 to 5The subjective value method was used to determine the raw scores. The raw scores for each of the candidates were assigned on the scale of: 5= superior, 4= good, 3= satisfactory, 2= weak, 1= Poor, 0= unacceptable.

KLT-40S

Mobility= 4 (KLT-40 is mobile thus good raw score)

Seismic= 5 (KLT-40S has 0.3g thus superior raw score)

Output= 4 (KLT-40S produces 35MW thus good raw score since power output required should be between 30- 100Mw)

Desalination= 4(KLT-40S has a desalination capability thus good raw score)

Weighted Score is calculated by using the following formula

Weighted Score = Weight)i * (Score)i

The selected system should have the physical architecture shown in the figure below.

3. Results

The results of the trade -off analysis are summarized in table 14

<Table 14> Summarized trade -off analysis

Evaluation Criteria	KLT-40S			VBER-150			NuScale			RIT			CNP-300			SMART		
	we gh	Score	Weighted Score	weight	Score	Weighted Score	weight	Score	Weighted Score	weight	Score	Weighted Score	weight	Score	Weighted Score	weight	Score	Weighted Score
Mobility	3	4	12	3	3	9	3	1	3	3	3	9	3	1	3	3	1	3
Seismic	5	5	25	5	4	20	5	5	25	5	5	25	5	4	20	5	5	25
Output	4	4	16	4	5	20	4	2	8	4	4	16	4	5	20	4	5	20
Desalination capacity	2	4	8	2	3	6	2	2	4	2	4	8	2	1	2	2	5	10
Weighted Sum			61			55			40			58			45			58

Comparing the weighted sums of the SMRs under consideration, KLT-40S scored significantly higher than the other designs. KLT-40S scored satisfactory in all the four performance criteria. It is worth noting that the cost was not considered in the criteria since the exact cost of each SMR could not be found. RIT model scored satisfactory in the seismic category and average in the three criteria and thus ranked second with 58 points while SMART also rated score 58 with the satisfaction of seismic and output power criteria.

4. Conclusion and Further Study

The development of architecture concept for BM SMR has been implemented using the systems engineering approach.

Evaluation of various SMR alternatives has been done using trade off matrix. The result shows that KLT-40S architecture concept has the highest weighted sum and therefore should be selected as the most preferred BM SMR for the project.

Further research is required for the validation of the design approach adopted in this work.

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