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# Concept definition of Small-Medium Reactor Coolant System using System Engineering

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Abstract : New design concept of Reactor Coolant System (RCS) including a reactor assembly for the SMR is introduced in this work. An exploration of new type of reactor that is advanced from proposed SMRs is performed by using systems engineering approach. In this point of view project structured on three main phases; needs analysis (NA), concept exploration (CE), and concept definition (CD). Main objectives as an output of the CE stage are a small size, low cost, shortening the schedule, and enhancing safety. The SMRs usually have a small size requirement. In order to meet the size requirement and to achieve a productivity, in other words, easiness to manufacture, this paper suggests an integrated PWR design concept through researching predecessors. Although the integrated PWR concept provides many advantages, it has disadvantages that composite of maintenance and a low availability problem. Therefore, this paper comes up with a run-to-fail design concept based on modular design to address the maintenance problem and to maximize the availability of SMRs as well as to be compatible with the overall-SMRs including Barge Mounted(BM) type.

*Key Words* : RCS, Barge, Run-to-fail, Integrated PWR, SMR, Availability, IDEF0, System Engineering

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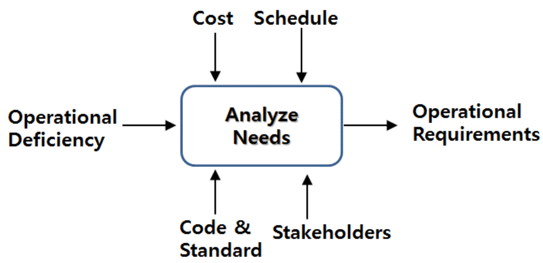
## 1. Introduction

A Reactor Coolant System(RCS) is an essential system for the nuclear power plant. The RCS has three major functions: transferring the heat from the reactor to the steam generator (SG), maintaining the pressure within acceptable limits, and the pressure boundary as one of the Defence-In-Depth(DID) functions. This work contains how the initial concept of RCS for the Barge-Mounted Small and Medium Reactor(BM-SMR) has been developed. It also includes a concept development phase and steps in the view of systems engineering. In this point of view project structured on three main phases; needs analysis(NA), concept exploration(CE), and concept definition(CD).

Throughout the needs analysis phase, we come up with some outputs such as identifying needs of stakeholders: an engineering management team, a licensing management team, a project management team, a power conversion team, and a reactor design team, to determine thermal power generation capacity for the power conversion of a turbine system to generate 100MWe and other safety and supporting features. At last stage, identified needs are validated and feasible concepts determined by needs validation. Main objectives as an output of the CE stage are a small size, low cost, shortening the schedule, and enhancing the safety in order to achieve a productivity, in other words, the easiness to manufacture, and also this paper suggests the integrated PWR concept and run-to-fail concept. Concept definition phase is supposed to include a preferred system architecture and definition of system functional specifications through synthesis of alternative systems. Activities conducted in this stage are performance requirements analysis, functional analysis, functional formulation, concept selection, and concept validation. By following those phases, functions are allocated to subsystems, concept decision will be made by trade-off analysis, and validity of chosen concept will be achieved.

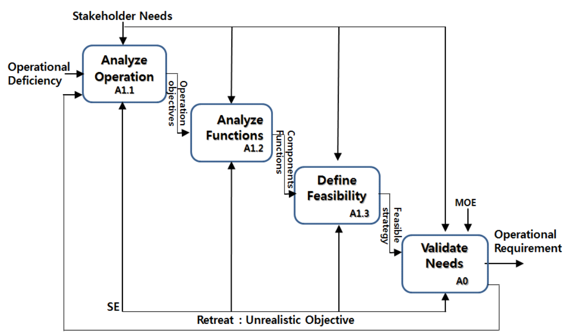
## 2. Needs Analysis

The needs analysis is a phase that is responsible for the determination of the need or desire for a new system. In this study, this is done using Integrated Definition Function model IDEF0 to show the activities involved in the needs analysis phase as shown in figure 1 [1].




[Figure 1] IDEF Level 1-1 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 in figure 2 [1].

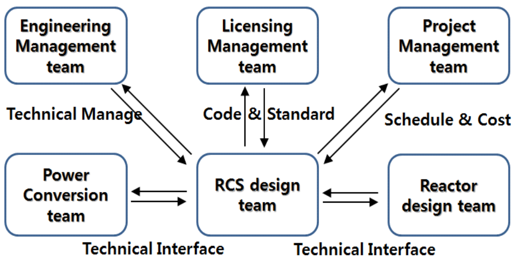



[Figure 2] IDEF Level 1 diagram for needs analysis

## 2.1 Operational Analysis

### 2.1.1 Stakeholder Identification

In this step, KINGS students with diverse discipline backgrounds represent the various stakeholder groups for the purpose of information gathering with knowledge in nuclear power plant development cycle stages were identified and tasked to identify stakeholders and played roles of stakeholders for each assigned tasks. Identified stakeholders were classified based on their interests and their power of influence to the success of this development project as shown in the figure 3 below [3].




[Figure 3] Identified Stakeholders

### 2.1.2 Analysis of Projected Needs

In systems engineering, a project can be either needs-driven or new technology-driven [1]. This work would be naturally categorized into needs-driven one with the given project conditions. Therefore, objective can be defined as below: "Providing Reactor Coolant System (RCS) for 330kWth Barge Mounted Small and Medium Reactor." According to Wikipedia [2], historically, these ship mounted reactors were purposed to provide propulsion power and there was no need to be connected to grid system, whereas this project is for generating electricity to supply power to a concerned community through grid system. In addition, motivations for SMR can be listed below [5]:

- Size of capital investment for large ALWR is too high for many power companies
- Fits into many electric grids better than large ALWR
- Shorter construction schedule matches better generation demand growth and provides early revenue stream
- Factory fabrication has potential for mass production with stable work force improved quality, smaller rework, etc.
- Sized to match replacement of retiring fossil generation
- Enhanced physical protection and robustness against external events because of underground construction, which can allow closer siting to electricity load centers
- Better suited to co-generation missions, e.g., desalination.

### 2.1.3 Operational Objectives

Starting from the objective, utilizing Utility Requirement Document(URD) and objective tree structure methodology shown in figure 4 and 5 respectively, the objective decomposed into five primary objectives as follows:

- Provide heat exchange capability
- Provide safety
- Comply with code and standards
- Manage cost under budget,
- Provide durable materials.

## 2.2 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 [1]. The functions are to be performed by each stakeholder.

#### 2.2.1 Translation of operational Objectives into System Functions

Each operational objective was translated into functions. Using the same numerical designation,

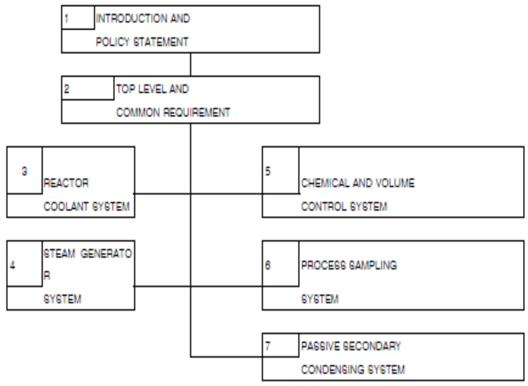
- Provide heat exchange capability
  - Transfer energy from heat source(i.e. core) to steam generating components
- Provide safety
  - Circulate reactor coolant using natural circulation
  - Provide cooling function whether normal or emergency operation
- Comply with Code and Standards
- Manage cost under budget
  : To achieve this, all systems, components, and structures (SCS) should be designed by using already existing components and modules on the market as much as possible.
- Provide durable materials: In order to maximize the availability and safety, all SCS should be made of durable materials under the budget.

#### 2.2.2 Allocation for function to Sub-Systems

The above identified functions can be allocated and combined into the subsystems that are analogous to existing legacy system.

### 2.3 Feasibility Definition

The feasibility is evaluated on the basis of the cost effectiveness [1] and the settled target is the productivity, the easiness to manufacture. The outcome of this process is more refined [4]. In order to minimize cost and enhance the safety, passive safety systems are employed as much as possible while observing the highest level of safety as defined in the licensing requirements and safety guidelines provided by the regulatory body. Furthermore, the project should adopt proven technologies, for examples, general development strategy, design approach, evaluation method, and production issue to avoid anticipated risks.



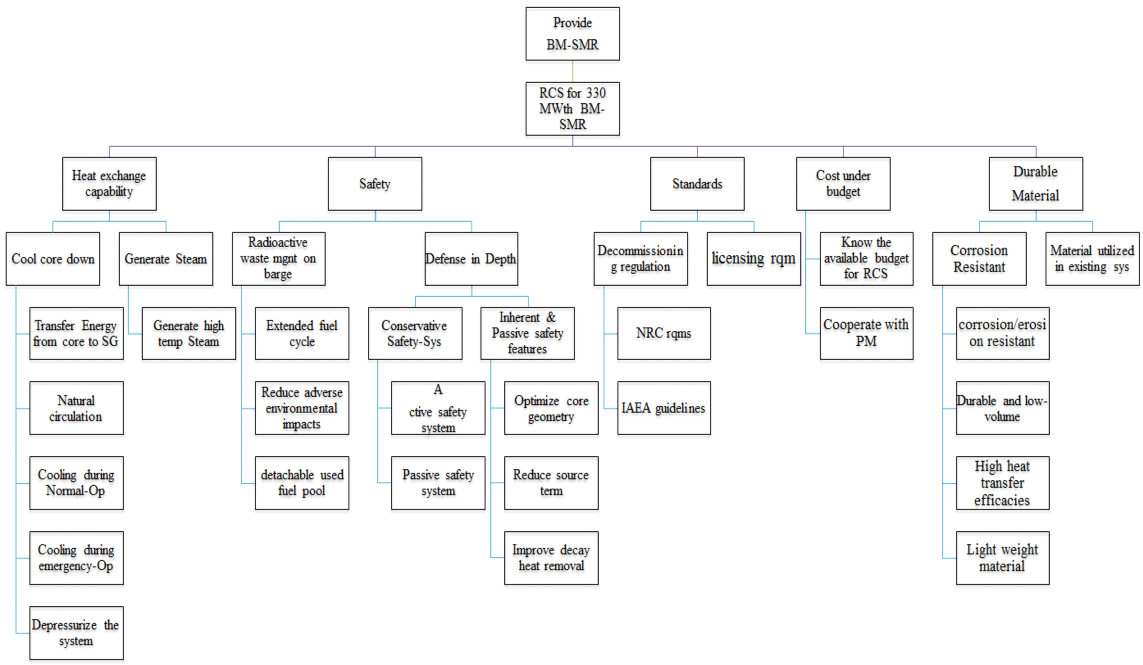

[Figure 5] Objective Structure

### 2.4 Needs validation

The validity of the process is evaluated on the basis of cost implication and the performance of the strategy. Therefore, there is a 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 [4].

#### 2.4.1 Operational Effective Model

Steam Generator's loops act as the primary barrier between radioactive(Primary) side and non-radioactive sides(Secondary) of the plant as the primary coolant become radioactive from its exposure to the core. Therefore, the tubes will be checked from time to time to ensure that they are in proper working conditions and to detect any leakage of water between the two sides of the plant. This can be achieved through

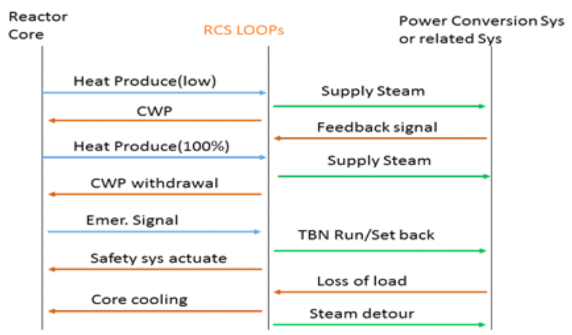



[Figure 4] Utility Requirement Document for RCS

the scheduled maintenance outages or shut downs for all Steam Generators by eddy-current testing. In operational mode, the loops produce superheated steam for full-range efficiency. In non-operational mode like maintenance, the loops can be accessed easily.

### 2.4.2 Operational Scenario

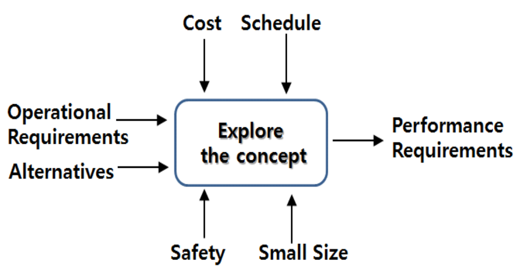
In line with the operational effective model for the operational mode, the operational scenario based on the stakeholder' s need analysis can be illustrated by using the figure 6 below:




[Figure 6] Operational Scenario

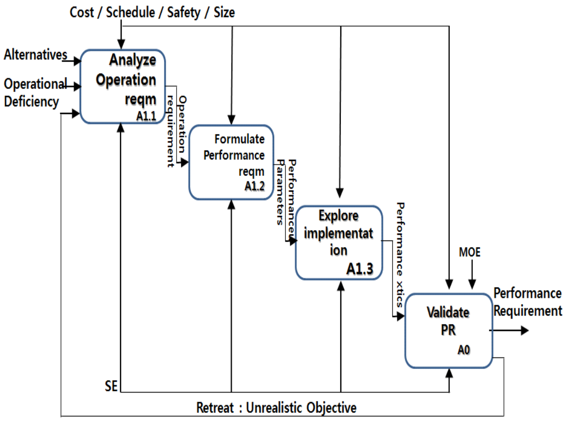
## 3. Concept Exploration

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 concepts 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 7 below [4]:




[Figure 7] IDEF Level 1-2 diagram for Concept Exploration

The activities performed in concept exploration can be decomposed further into sub-functions to enhance the understanding of the interactions involved in terms of inputs, enablers, controls, and outputs [4]. This decomposition is shown in the figure 8 below:




[Figure 8] IDEF Level 1 diagram for Concept Exploration

### 3.1 Operational Analysis

This step evaluates the completeness and consistency of the operational requirements. It uses the initial set of operational requirements, the operational scenario showing the environment of operation of the system. In the previous need analysis phase, the operation requirements had been settled. In order to analyze these objectives of RCS, we settle the criteria and restating the operational requirements as listed below:

- size that a barge ship can accommodate
- cost
- schedule
- safety

We did analyze those requirements, to assure compatibility with other related systems, with power-conversion team and reactor team and then reached the conclusion that the restated requirements are reasonable.

### 3.2 Performance Requirements Formulation (Functional Definition)

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 an attempt to satisfy the operational requirement, many options can be proposed from which the best alternative should be chosen. The output of this process is performance parameters [1]. In this step, we tried to translate operational requirements into RCS and sub-system functions which are associated with RCS. The functions of RCS provide small size to install the barge ship or smaller site than a conventional nuclear power plant site, as well as delivering heats from the reactor to the steam generator, reducing the cost as much as possible, keeping the mile-stone schedule, and guaranteeing the safety features. As a result, the performance requirement formulations are described below:

1) Availability goal: greater than 90%
2) Unplanned trip: less than 0.8/yr
3) Load follow
   - Daily load follow capability
     - 16(100%) - 2(100%-50%) - 4(50%) -2(50%-100%)
   - Unplanned power change capability
     - ± 10% step change
     - 5% ramp change /min
4) Load rejection capability
   - 100% load rejection without reactor trip
   - Pick the house load at grid fault
5) Refueling interval: 36 months
6) Maintainability
   - standardize the components and equip-

ment

• consider maintenance environment

### 3.3 Implementation Concept Exploration (Physical Definition)

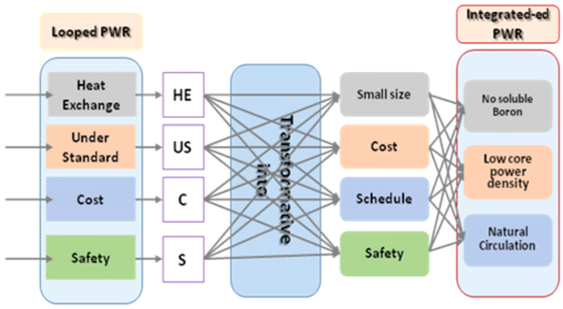
In this step, the feasible implementation technologies and concepts with the stakeholder who is the reactor design team are discussed. After that, RCS team and the reactor design team, reached a conclusion of adopting new technologies [5] and concepts as a sort of functional description which are:

<Table 1> Loop PWR vs Integrated PWR

| | Loop PWR | Integrated |
|---|---|---|
| Hot leg | Yes | None |
| Cold leg | Yes | None |
| RCP | Yes | Integrated |
| S/G | Yes | Integrated |
| PZR | Yes | Integrated |

- No soluble boron technologies
- Low core power density (Lower fuel temperature than looped PWR)
- Natural RCS loops circulation (Passive system concept)

and "Integrated type PWR concept" as an alternative concept with conventional looped reactor concept and we can call input and output identification method. According to this method, we could adopt integrated system concept from the conventional looped PWR. Additionally, this also to support this concept. These allow us to reduce size, cost, and keep the schedule and improve safety.




[Figure 9] Input and output identification method

### 3.4 Performance Requirement 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 or retreat to the operational analysis for re-evaluation since strategies may not be able to meet the operation requirements [4].

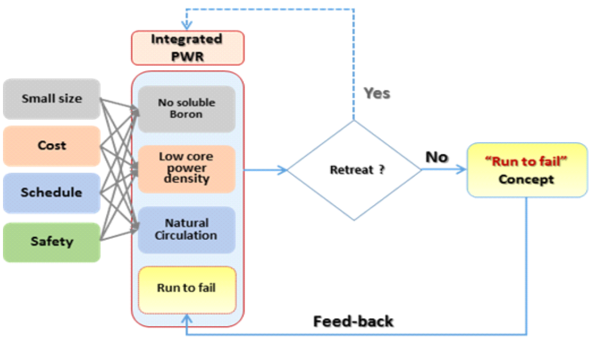
In order to conduct design validation and effectiveness analyses to accommodate the full range if desirable system concepts and technologies validation for the conformity or refining these requirements we did validate in terms of feasibility criteria coming up with previous step.

<Table 2> Tailored value matrix for Decision Making

| | Integrated Reactor | No soluble Boron | Low core power density | Natural Circulation |
|---|---|---|---|---|
| Size Reduction | High | Medium | Low | Negative |
| Cost Reduction | High | Low | Medium | Negative |
| Shortening Schedule | High | High | Low | Negative |
| Increasing Safety | High | Low | Low | High |

The tailored value matrix is shown above, after conducting validation and effectiveness of one concept and three technologies. This result table shows that the design concept, Integrated

PWR, and the technologies are good for over all criteria except for the natural circulation technology. Even though the natural circulation has negative effects on some categories, this technology heavily contributes, because it can cool down the reactor without the power, to safety. Through a trade-off decision making process based on a tailored value matrix for decision making. The natural circulation technology is therefore adopted. Even if this integrated loop concept with related technologies provides lots of advantages, it has disadvantage that is related with maintainability. This concept does not have enough space for maintenance because maintenance workers and equipment will not easily access RCS. Thus, we have to decide whether retreat of formulating the new concept to deal with this obstacle.



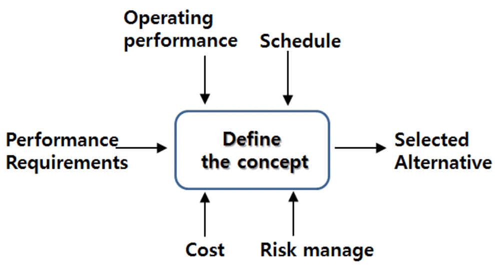

[Figure 10] Decision making process by using tailored input and output identification method

To overcome this obstacle, this paper proposes to introduce a new concept "Run-to-Fail" and then incorporated this Run-to-Fail into Integrated PWR.

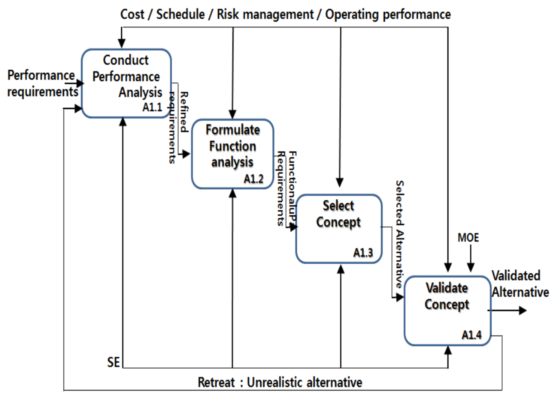
## 4. Concept Definition

This phase marks the beginning of serious work of defining the functional and physical characteristics. The selected alternative is supposed to meet all the refined operational needs as described in the preceding conceptual phases. The process is described by using an IDEF0 Level 1 diagram shown in figure 12 and 13. 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 [4].




[Figure 12] IDEF0 Level 1-3 diagram for Concept Definition




[[Figure 13] IDEF0 Level 1 diagram for Concept Definition

Easy to manufacture guarantees the operating performance. First, easy to manufacture allows the operating performance and compatibility to be adopted, in other words, the systems we want to incorporate into our intended SMR we can easily be supplied by many vendors and also the products they produced already are proven. Secondly, Cost, most components consisting of our system are already on the market. It means we can purchase at a reasonable price better than specially manufactured sub-system and components. Next, Schedule, easy to manufacture expedites acquiring the base resources to make our system. And also, we can reduce the risk by using the things they already were passed under EMI-EMF inspection and Q-class or nuclear qualification like KEPIC. In addition, high compatibility convinces our system for easy maintenance and marketability.

## 5. Conclusion

Throughout this work, the new design concept for the RCS including a reactor assembly for the SMR is introduced. Firstly, the MBSE concept is applied which consists of the concept exploration using IDEF0 level 0, and the concept definition using IDEF0 level 1. Secondly, the methodology to select the alternative using decision making process by tailored input and output identification is also implemented. By combination of those methods, the new "Run-to-Fail" concept based on modular design for designing the RCS system can be introduced. The proposed method can satisfy the following design factors such as cost, schedule, and risk factor management method. In association with major decision making process by using tailored input and output identification method, the competitive edge against the currently proposed RCS design can be achieved. Even though this work deals with the conceptual design of new RCS, but it is believed that this is the starting point for improving the capabilities of the design. Further study will be executed to justify a lot of assumptions which are discussed in this work.

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