Configuration management of design requirements for nuclear fuel cycle facility

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Abstract

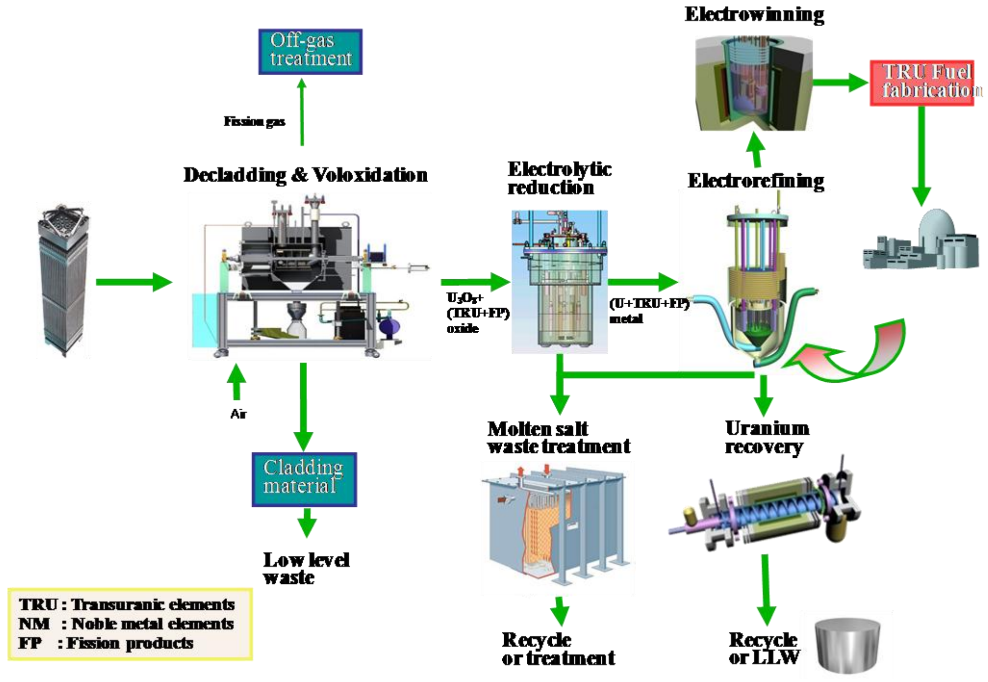
This study introduces a system that can confirm whether all requirements are satisfied, by systematically managing the highest design requirements to the requirements for the lowest unit devices of the PRIDE (PyRoprocess Integrated inactive DEmonstration facility) facility through mutual relationships, and effectively tracing the influences of the requirement changes. To carry out the technology traceability based on pyroprocess facility design data and research result data, a database system is proposed that can manage extensive amounts of data. This paper explains the procedure for developing a pyroprocess system engineering framework and data schema with respect to configuration management. To confirm whether the technology traceability is carried out within a reliable boundary based on the top requirements, system requirements, sub-system requirements, and component requirements of the derived PRIDE system, the experiment was performed with an Ar (Argon) cooling system, which is an important device. As a result of verifying the validity of the technology traceability with sample data input, it was confirmed that, when the pyroprocess separation process is designed in an inert (Ar) gas atmosphere, from the top requirements of the pyroprocess to the capacity and electricity of the chiller unit (which is the unit process device composing an Ar cooling system), the requirements can be effectively traced.

Introduction

The Korea Atomic Energy Research Institute (KAERI) has been developing a strategy for implementing a pyroprocess that includes sodium fast reactor (SFR) fuel cycle to achieve more efficient and effective spent fuel management. KAERI will construct PRIDE to evaluate the performance test using natural uranium for the pyroprocessing.

The PRIDE facility handling the spent fuel is a complex facility with the highest priority in terms of economic feasibility and stability, unlike general industrial facilities. Pyroprocess technology is mainly classified into 3 processes, a head-end process, a pyroprocess separation process, and a system engineering process. Figure 1 shows the pyroprocess flow diagram of the PRIDE facility. To minimise the waste of budget and time caused by an increase in cost by mismatching the design and system definition, delay in the construction schedule/delivery, and reworks, the technology traceability shall be secured from the highest design requirements down to the process device design of the sub-system before the stage of the construction, and through this, a change in management can be carried out systematically.

Figure 1: Flow diagram of the pyroprocess separation process in the PRIDE facility



Configuration management (CM) is the process of identifying and documenting the characteristics of a facility's structures, system, and components, and of ensuring that changes to these characteristics are properly developed, assessed, approved, issued, implemented, verified, recorded, and incorporated into the facility documentation. CM processes correctly applied ensure that the construction, operation, maintenance, and testing of a physical facility are in accordance with the design requirements as expressed in the design documentation. An important objective of a configuration management programme is to ensure that accurate information consistent with the physical and operational characteristics of the nuclear fuel cycle facility is available in a timely manner for making safe, knowledgeable, and cost-effective decisions with confidence.

As engineering requirements, the basis of a decision support framework for the design and different components of risk-management strategies in risk-critical systems such as a nuclear power plant or off-shore oil platform has been presented in [1]. In the configuration management, a method by which all plants (those under construction, as well as those in operation) can benefit from a formal, step-by-step approach to data capturing, storage, and retrieval for use throughout the plant life cycle has been presented by Paul R. Smith [2].

This paper introduces a system that can collectively manage the pyroprocess task process and system consolidation, pyroprocess information sharing and collaboration through communication in a unified system, and the visibility of research and project management tasks with the goal of successfully establishing PRIDE. It explains the pyroprocess engineering system that enables the systematic and scientific analysis of the requirements of the stakeholders on the full life-cycle of the pyroprocess system and technology traceability for the successful establishment of PRIDE. It also introduces an analysis and decision method to systematically analyse the traceability. A pyroprocess engineering system is customised using CRADLE® software. All engineering data used in the pyroprocess design and configuration management results are managed in a single database, which cope with both pyroprocess system engineering and task management.

Pyroprocess system schema and requirements

Procedure of pyroprocess schema

A schema indicates a database structure. Currently, most computer supported system engineering tools use a database management system. However, the types of data to be used in each project are different according to the target system or organisation, and thus it is common to design schema to develop in computer support tools. This schema includes the types of the data to use the attributes of all data, and the relationships among the data. A computer support system engineering tool, Cradle®, was used to develop the schema. The following are the detailed contents for pyroprocess system engineering schema establishment procedure.

Definition of the PRIDE facility task area

There are two main reasons for defining task areas; first, to facilitate distinguishing tasks in the next stage, and second, to establish a master tree for easy data access from tools. It is common to classify task areas into system development stages such as design, development, establishment, and management, but classifying on the basis of years or teams may be effective in some cases because of the characteristics of the task.

Definition of the PRIDE facility task

A task definition defining the name of the task to be carried out from each task area defined above. The level of the task shall be defined as a level that can be expressed with a single element in the tools. That is, requirement management, risk management, and verification requirement management are examples.

Definition of the PRIDE facility detail task contents

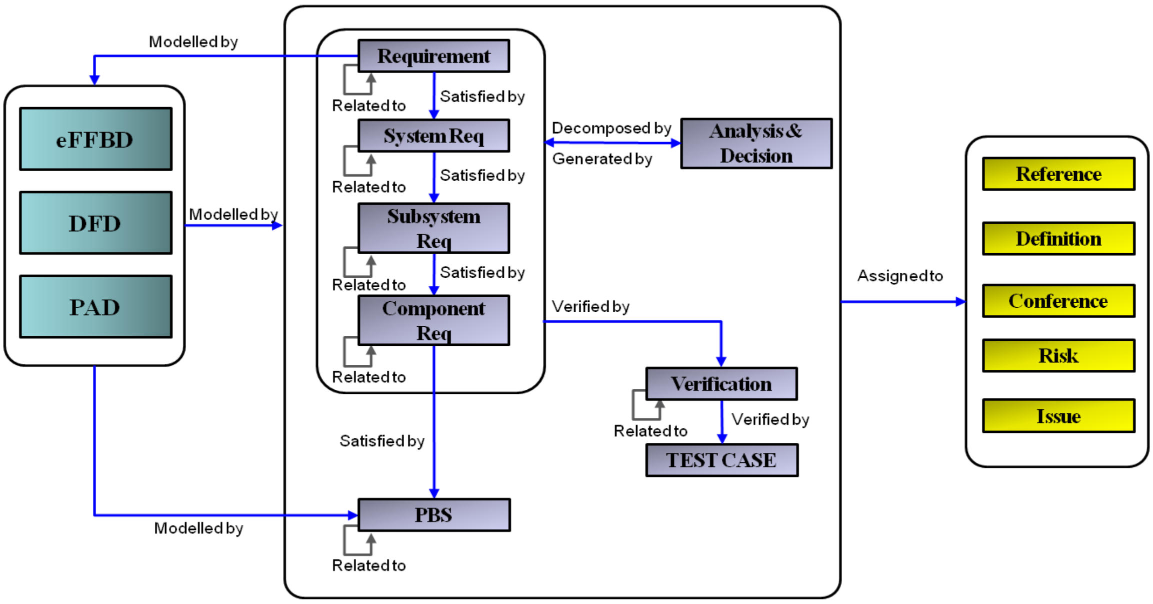
Detailed task contents defining the detailed contents of the defined tasks are defined to a level corresponding to the attributes of an entity. In the case of the top requirements, the detailed attributes are defined with name, management number, item status, security classification, contents of the requirements, reason for the selection, remarks, etc. and related files are able to be attached. Also, if there is a need to record the contents of a meeting related to requirements, you can set the relationships with requirements, minutes of the meetings, etc. When such detailed tasks are defined, in an organisation or project with well-defined tasks, the defined contents are usually contained in the tools, but the parts not defined well in the tasks of the organisation are also supplemented and defined with reference to the basic schema installed in the tool.

Schema of pyroprocess system engineering

The entire schema of the pyroprocess system engineering framework developed in this task is shown in Figure 2. The explanations for each element are as follows.

- Requirement: the top requirement is a customer requirement related to the system development or a declarative requirement related to the task.

Figure 2: Schema of the pyroprocess system engineering framework



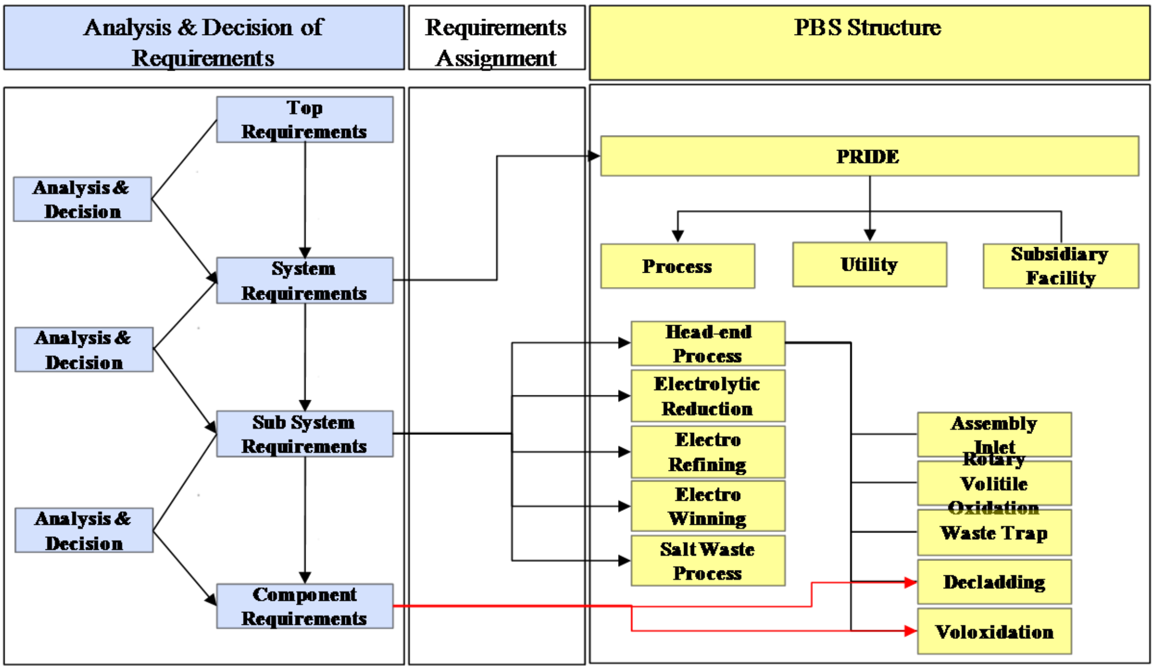
- System Requirement: the system requirement is the requirement defined through an analysis and decision for the top requirement and the system requirement is stated in technical language, while the top requirement is stated in natural language.
- Sub System Requirement: the sub system means the elements composing the utility, process, and subsidiary facilities. System requirements are disassembled into sub system requirements.
- Component Requirement: a component means the elements composing the sub system. The sub system requirements are disassembled into component requirements.
- Analysis and Decision: analysis and decision-making are the efforts to disassemble the upper level requirements into lower level requirements. An analysis and decision forms the basis of technology traceability. All requirements shall be linked to the analysis and decision.
- Product Breakdown System (PBS): a system is composed of a layer structure. Disassembled requirements are assigned to the PBS elements. Through such a process, we can verify whether all requirements are developed into an actual product.

- Verification: verification requirements state the method to verify the requirements and completion standards. All requirements shall have verification requirements. Verification requirements form the basis of the test criteria to be actually carried out.
- Enhanced Functional Flow Block Diagram (eFFBD), Data Flow Diagram (DFD), and Physical Architecture Diagram (PAD) are used to clearly show the contents that are hard to understand with text, through modelling. eFFBD is used to express the execution order of the functions according to time, DFD expresses the data interface between each function, and PAD is used to express the physical structure of the system.

Traceability using analysis/decision

Traceability is a discernible association among two or more logical entities such as requirements, system elements, verifications, or tasks. Also, complete and thorough requirement traceability is a critical factor in the successful validation of requirements. Figure 3 shows the concept of the technology traceability. The requirement analysis and disassembly parts in this figure are generally called requirement traceability. That is, it shows whether the top requirements are developed down to the lower level requirements. However, technology traceability shall include not just the contents of simply disassembled requirements, but also the development process. This is the analysis and decision part shown on the left side of the above figure. Through such an assignment process, you can find which requirement shall be satisfied for each component. The core of such technology traceability is the answer to 'why'.

Figure 3: Schema diagram of traceability and requirements analysis and decision



Deriving pyroprocess system requirements

The requirements are the basics of all projects, and they generally include essential functions and performance to be carried out by the system, restrictions by law. The agreed requirements become the basis for establishing a system development plan, and they also become the basis for taking over the developed system when the project is completed. A pyroprocess system is mainly composed of the safety design of the utility and structure, facility and process devices including radiation safety design, and subsidiary equipment necessary for pyroprocess separation process operation and maintenance. Since a pyroprocess facility is a particular facility handling spent fuel, it shall satisfy safety-related legal requirements. The requirements to be complied with, related to the safety of a nuclear fuel cycle facility such as PRIDE, are explained in detail in the following documents. The approach taken by two Fluor Hanford projects for implementing the seismic design criteria has been described by S. K. Omberg [3]. The need to minimise security risk, proliferation hazards, and safety risks in the design of new nuclear facilities has been emphasised by Robert S. Bean [4]. Institutionalising Safeguards-by-Design (ISBD), that is, the implementation of a structured approach by which international and national safeguards, physical security, and other non-proliferation objectives are fully integrated by means of a Safeguards-by-Design (SBD) process into the overall design and construction process for a nuclear facility, from initial planning through design, construction, and operation, has been conducted by T. Bjornard [5]. The non-reactor nuclear safety design criteria and explosives safety criteria guide provide guidance on the application of requirements for non-reactor nuclear facilities and explosives facilities of the Department of Energy (DOE)420.1, FACILITY SAFETY, Section 4.1, Nuclear and Explosives Safety Design Criteria U.S Department of Energy [6].

Case study: Traceability of the Ar cooling system requirements of PRIDE

A System for Pyroprocess Integrated Requirement Engineering (SPIRE), which can manage PRIDE research/project information, trace the relationship between unit process devices, and easily manage the changes, is under development. SPIRE is classified into system engineering/requirement management and project management. System engineering/requirement management manages the top requirement, system requirement, lower level system requirement, and component requirement, and project management manages the schedule, budget, manpower, and tasks related to the research/project. In this paper, the validity of the framework is verified through the input of the sample data of Ar cooling system, which is one of the important factors of the pyroprocess facility. In an air cell atmosphere, salt replacement becomes very difficult due to deliquescent salt, and the deliquesced salt becomes a strong corrosive liquid, making stainless steel structure easily corroded. To solve such a problem, an Ar atmosphere device is necessary.

Selecting top requirement for each function

The top requirement states the requirements or tasks presented by the user in relation to the pyroprocess system development. In this paper, a total of 13 top requirements were selected with the PRIDE system as the target. The system requirement is written through an analysis and decision on the top requirement. That is, it defines the requirements that the system shall be equipped with to satisfy the top requirement. In this paper, technology traceability is secured through the input of such disassembly process selectively for the defined top requirement.

PRIDE system requirement management

An analysis and decision show the most basic contents of technology traceability. The top requirement is “the system shall be able to separate uranium and transuranium elements through the pyroprocess separation process such as electrolytic reduction, electro refining, and electro winning”. To satisfy such a top requirement, the contents of the analysis and decision on whether an inert gas atmosphere is appropriate are described, and through this, the system requirement, “the system shall have all the processes to be carried out in Ar atmosphere to prevent corrosion of hotcell device” is defined. The requirement management is composed of 2 parts: requirement traceability management and change management. Requirement traceability is generally managed bi-directionally. One is downward traceability, and the other is upward traceability. Downward traceability is used to verify whether all top requirements are disassembled and developed into component requirements, and upward traceability is used to verify if a component or downward sub system requirement is based on the system requirements or top requirement. If downward traceability is missing, then the requirements that are not disassembled will be disassembled, and if upward traceability is missing, then the top requirement will be created or it will be decided whether the corresponding requirement is essential, and if it is unnecessary, it will be removed to prevent an excessive design.

A downward trace table related to the Ar cooling system requirement of PRIDE is defined. The top requirement for the capacity, electricity, and type of chiller unit composing the Ar cooling system is presented. If the design is changed in relation to the Ar cooling system during the construction period, we can see how the requirement will change from the initial AR cooling system requirement after the change, and furthermore, decide how the top requirement of the PRIDE facility shall be changed through this information. Requirement change management is not separately carried out, but is carried out using the history management function of CRADLE.

Conclusion

Pyroprocess system engineering and project management technology are high value technologies with a large technical ripple effect towards the nuclear power and general industries, and thus will be born again as a competitive technology that can greatly contribute to the nuclear power industry as a technology that can guarantee the safety and economic feasibility of nuclear power plant facility construction and safety measurements.

For the successful development of the PRIDE facility, which is one type of nuclear fuel cycle facilities, SPIRE (system engineering framework) was developed, and a schema designed to be suitable for pyroprocess facility construction is embedded in this framework. To verify the validity of technology traceability using the system engineering technique in the developed SPIRE system, as a result of an experiment using sample data input, we can verify that it matches precisely the top design requirement of the pyroprocess to the chiller unit process of an Ar cooling system.

This technology has the advantage of being able to verify the project progress status in real time, and thus recognising a problem becomes possible in advance to support decision making based on reliable data, and an easy objective evaluation of the project.

Acknowledgements

This work was supported by the Nuclear Research & Development Programme of the National Research Foundation of the Republic of Korea (NRF) funded by the Ministry of Education, Science & Technology (MEST).

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