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Considerations on Deploying Systems Engineering to Accelerate the R&D of New Nuclear Fuels

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Abstract—A project for the research and development (R&D) of new nuclear fuels is a system with the following characteristics: having large number of stakeholders, progressing through a set of life cycle stages, validated by advanced measures of effectiveness, integrating multiple disciplines and specialty groups, and facilitated by enabling systems, thus can be effectively managed with the approach of systems engineering (SE). In this paper, the deployment of SE in global nuclear industry including Russia, the U.S., France, Korea and China is reviewed. By learning the experience of SE deployment in global nuclear industry, the SE characteristics of projects for the R&D of new nuclear fuels are analysed based on systems science. The R&D projects of medical cobalt adjuster rod assemblies and mobile nuclear reactor in China North Nuclear Fuel Co., Ltd. (CNNFC) are discussed as SE practices. It is proposed that in order to accelerate the R&D of new nuclear fuels in nuclear fuel manufacturing plant, SE should be enhanced in the following aspects: adhering to systems science, making good use of SE engineers, introducing SE tools, and exploring SE characteristics.

1 Introduction

Nowadays, the third or fourth generation nuclear energy systems are pursuing for higher generating efficiency, wider industrial use, stronger economic competitiveness and inherent safety and passive safety features. The research and testing reactors have also been continuously developed for validating new reactors, material research, material irradiation, isotope production and other purposes. Both commercial and research nuclear power plants (NPPs) have set higher requirements on the economic property, safety and reliability for nuclear fuel. Only by developing new nuclear fuel to meet the needs of advanced reactors as well as for independent innovation of nuclear power can we catch up with the advanced levels of nuclear fuel research and development (R&D) in the world, meet the future national economic R&D and national energy security needs, seize the opportunity in the future international competition, and provide fuel technology services for advanced reactors or research and test reactor to “go global”.

A project for the R&D of new nuclear fuels can be considered as a system, thus can be managed with the methods of systems engineering (SE). SE first originated in Bell Telephone Laboratories. Since World War II, it has been increasingly applied to the R&D of aircraft, military equipment, rockets, satellites and other systems with sheer size, numerous requirements, leading technology and complex interfaces [1]. Aircraft systems, in particular, which have a wide variety of models, require certification and mass-productivity after successful development, and are particularly suitable for life-cycle process management using a SE approach. Therefore, SE has received the most attention and is widely used in the aeronautics and astronautics field at home and abroad, such as the National Aeronautics and Space Administration (NASA), the U.S. Department of Defense (DoD), the Federal Aviation Administration (FAA), the U.S. Navy and the Air Force have developed SE manuals, Boeing and Airbus have carried out good SE practices, and Aviation Industry Corporation of China (AVIC), Commercial Aircraft Corporation of China (COMAC) are also actively promoting and implementing SE in China.

Nuclear industry is a strategic high-tech and typical closed chain industry requiring large investment, long cycle time, and its social impact is wide and safety requirements are strict [2]. Similar as the aerospace industry, new NPPs also need to be licensed in a condition of meeting regulatory requirements. Noticed the fact that military and civilian aircraft are different and the fact that aeronautics and astronautics are not the same, there are different needs for reactors, nuclear fuel using, reprocessing work and nuclear technology application. As a result of this, nuclear industry should not blindly copy the successful experiences of other industries, but should develop and apply SE approaches with nuclear industry characteristics.

Some aspects of SE, such as demand management, have been incorporated into the regulatory requirements

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concerning nuclear power in some countries (e.g., Finland). However, the practice of applying SE to the nuclear industry is still relatively insufficient around the world, not to say the R&D of new nuclear fuels. Meanwhile, in China's nuclear industry, systems science and SE methods have also been applied to some extent, and multiple studies have been conducted on the reactor models, reliability of operators and safety systems, and value engineering of nuclear engineering. But it is not until recent years that NPPs, nuclear fuel R&D and manufacturing or reprocessing engineering are deemed as complex systems with life cycles, based on the life cycle model and Vee model.

This paper first reviews the SE practices in the nuclear industry around the world, then analyses the characteristics of nuclear fuel research and production. The R&D projects of medical cobalt adjuster rod assemblies and mobile nuclear reactor in China North Nuclear Fuel Co., Ltd. (CNNFC) are discussed as SE practices. Finally, some suggestions are proposed on how to use SE approaches to accelerate the new nuclear fuel R&D.

2 SE models and practices in nuclear industry

2.1 Early practice of SE in nuclear industry

Looking back into the history of the nuclear industry, some empirical characteristics of SE had been displayed as early in the Manhattan Project in the United States: first, human, material and financial resources were highly centralized for unified mobilization; second, armed forces, universities and laboratories were united; third, demilitarized management was adopted on scientists and laboratories to ensure academic discussion at liberty; fourth, the whole project was highly confidential, which means that most people only had access to some of the sub-systems, being unaware of the purpose of the program.

2.2 Life cycle stages of NPPs

Figure 1 compares the life cycle models adopted in nuclear industry. As for commercial NPPs, generic life cycle can be divided into 10 stages [3]. In design stage (*), State Atomic Energy Corporation Rosatom (ROSATOM) is implementing the so-called VVER-TOI™ initiative, whose goal is a new NPP unit design (VVER technology based), of which the NPP unit development system (NPPDS) is considered to be the key tool of the NPP life cycle management [3]. NPPDS is a "system of systems" (SoS), which comprises several design and development organization entities as well as different software systems used by those entities, each of which is a system in and of itself. The life cycle stages of VVER TOI™ initiative include proof of concept, requirements analysis, design, and validation & verification. The NPPDS architecting process consists of the following stages: determining the stakeholders; defining the stakeholders' concerns; development views and models to cover all concerns; architecting and architecture description development.

Generic life cycle (ISO/IEC/IEEE 15288:2015)

Concept stage	Development stage	Production stage	Production stage	Utilization stage	Retirement stage
				Support stage	

Life cycle of the NPP [3]

Feasibility study	Site selection	Design*	Construction	Commissioning	Utilization	Modernization	Decommissioning	Demolition	Site rehabilitation

Stages of the VVER-TOI^{TM} Design by ROSATOM [3] (stages of Design*)

Proof of concept	Requirements analysis	Design	Validation & verification

Replication of the VVER-TOI^{TM} NPP by ROSATOM [3] (stages of Design*)

Employing the VVER-TOI^{TM} Design	Tailoring	Completing

Stages of NGNP high-level project by INEEL [4]

Initiation (pre-conceptual)	Conceptual	Preliminary design	Final design	Construction	Operations/testing

Stages of the DCS project by CNNP Guodian Zhangzhou Energy Co., Ltd. [5]
(1) In quality management:

Planning stage	Requirement stage	Design stage	Implementation stage	Test stage	Installation and commissioning stage

(2) In project management:

Upstream design stage	Downstream design stage	Design information providing and clarification stage	Engineering design stage	Production stage	Factory test stage	Acceptance and delivery stage

Stages of new nuclear fuels R&D projects in CNNFC

Research experiment (technological demonstration) stage	Small batch trial production stage	Product trial production stage

Stages of the R&D of new nuclear fuels proposed in this paper

Project approval	Design	R&D	Manufacturing	Irradiation testing	Operation

Fig.1 Comparisons of the life cycle models adopted in nuclear industry

Idaho National Engineering and Environmental Laboratory (INEEL) proposed a SE framework for design, construction and operation of the Next Generation Nuclear Plant (NGNP) [4]. It is believed that to effectively manage this multi-organizational and technologically complex project whose technological and organizational challenges are complex, SE techniques and processes will be used extensively to ensure delivery of the final product. The life cycle of NGNP is divided by INEEL into six stages: initiation (pre-conceptual), conceptual, preliminary design, final design, construction, and operations/testing。

CNNP Guodian Zhangzhou Energy Co., Ltd. (CNNP Zhangzhou) [5] reported the application of SE approach in the Distributed Control System (DCS) project of HPR 1000 (Hua-long Pressurized Reactor). The life cycle in quality management of this project is divided into planning stage, requirement stage, design stage, implementation stage, test stage, and installation and commissioning stage, while the life cycle in project management is divided into upstream design stage, downstream design stage, design information providing and clarification stage, engineering design stage, production stage, factory test stage, and acceptance and delivery stage

2.3 SE methods adopted in NPP design and construction

The stakeholders of NPPs determined by ROSATOM include plant owner/operator, plant designer(s), nuclear steam supply system designers, scientific R&D entities, construction entity (or entities), PDS users, PDS integrator/developer and software vendors. Processes and Functions view, Organizational Structure view, Information Systems view and Data view are developed based on Capital Project Architecture Framework (CPAF) viewpoints.

The SE approach summarized by INEEL for the NGNP include: creation of seamless management, focus on advanced NGNP development, create problem-solving environments, encourage strategic alliances and collaboration.

Thales Group and Framatome presented a SE case study where model-based systems engineering (MBSE) methodologies was applied under real-life conditions [6]. In that case, pressurized water reactors (PWR) were divided into nuclear island (NI) system (as their system-of-interest) and the conventional island (CI), and the NI system. First of all, the main operational mission and the architecture tradeoffs of NI were analyzed. Then, Arcadia engineering perspectives (as their MBSE methodology) was tailored to cope with specific tasks. Later, system functional analysis and logical analysis were performed on NI with Arcadia perspective and Cappella model. This case shows benefits both in supporting the technical production and in the daily interactions between engineering teams.

KEPCO International Nuclear Graduate School (KINGS) performed a SE approach for multi-physics load follow simulation of APR1400 [7]. In that case, the requirements, functions, and physical architecture were identified by SE approach, and a set of verification and validation activities that guide the project development by linking each requirement to a validation or verification test with predefined success criteria was provided.

CNNP Zhangzhou is a typical representative in the practice of SE in China. CNNP Zhangzhou applies SE approach in the DCS project of Zhangzhou Nuclear Power Plant Unit 1 and 2 in the batch construction of HPR 1000. A complete element structure of project management was developed through the breakdown and analysis focusing on the seven stages, seven fields and seven management elements of DCS project management, which means “see both the forest and the trees” from the perspective of SE. Vee model was applied throughout the whole process of quality management. Through further practice and summary, these SE methods are proved to be worthy of application in the DCS project management of future HPR 1000 batch nuclear power projects, and can be launched for the project management of other long-cycle main equipment of nuclear power plants, thus to realize the goal of “cost control and schedule optimization”.

China Nuclear Power Engineering Co., Ltd. [8] analyzed NPP design management, pointing out that it is composed of design planning, design interface, design progress, design analysis, design change and other essential factors. It was found that systems thinking is reflected in the “two command lines” - administration and technology, in the management in design stage, and in the management of accident conditions. It was pointed out that SE is insufficiently launched in the organization system, top-down design process, design interface management, design verification, etc. Several suggestions were put forward on the better application of SE in the NPP design.

In addition to the design of NPPs, SE research related to nuclear engineering also includes the research on the role of nuclear power in national defence, energy security, and resistance to climate change [9], SE education in university nuclear majors [10], etc. It can be seen that Russia, the United States, France, Korea, and

China are leading the world in the application of SE in the nuclear industry.

2.4 SE methods adopted in the whole industrial chain of nuclear industry

Apart from NPPs, China Institute of Atomic Energy [11] analyzed the reprocessing engineering of nuclear fuel, which was pointed out to have the main characteristics of SE, such as wholeness, relevance, and coordination, and proposed a SE approach for system environment analysis, system function analysis, system analysis methods and contents, and evaluation and decision making.

In summary, SE is found to be mainly applied for reactor design and manufacturing in nuclear industry. However, it has not been used in other parts of the industry chain, and there is no report on the application in the R&D of new nuclear fuels yet.

3 SE features and practices of new nuclear fuel R&D projects

3.1 SE features of new nuclear fuel R&D projects

In order to better apply SE in new nuclear fuel R&D and manufacturing, the analysis of the features of new nuclear fuel R&D projects is firstly performed. Through integrating the theory and practice, the following features of new nuclear fuel (including the targets for isotope production) R&D projects are proposed:

(1) Having large number of stakeholders. Nuclear power plants are direct users of nuclear fuels. For the nuclear energy system represented by reactors, nuclear fuels are just one of its subsystems. On the other hand, in the case of taking the whole industrial chain of nuclear industry as a system, nuclear fuel manufacturing is also linked with design, procurement, testing, reprocessing and others. Accordingly, the stakeholders concerning nuclear fuel also include design institutes, raw material suppliers, workers of manufacturing, reprocessing plants, regulatory authorities and the like.

(2) Progressing through a set of life cycle stages. At present, CNNFC divides its research projects into three research stages: research & experiment (technology demonstration) stage, small batch trial stage, and trial production stage. For the approval of a research project, there are also three stages: preliminary preparation, project declaration and project approval. With reference to ISO/IEC/IEEE 15288:2015, ROSATOM, INEEL and the life cycle processes of the U.S. Department of Energy (DoE), new nuclear fuel R&D projects can be divided into major stages including project approval, design, R&D, manufacturing, irradiation testing, and operation, and the stages can be subdivided under the major stages.

(3) Validated by advanced measures of effectiveness. The use of nuclear energy goes after higher safety, reliability and lower cost, and during the service, nuclear fuels face coupling effects of high temperature, high pressure, strong irradiation and stress condition, which requires comprehensive measures of effectiveness. Compared with other industrial sectors, the nuclear industry is characterized by high environmental sensitivity and social concern, and therefore safety plays a crucial role, which puts forward higher requirements for new nuclear fuel design and manufacturing technologies.

(4) Integrating multiple disciplines and specialty groups. Nuclear fuels can be divided into fuel, cladding and other subsystems, and the whole process technology of nuclear fuel research and production involves chemical engineering, metallurgy, powder metallurgy, pressure processing, welding, surface treatment, machining, irradiation testing, detection and characterization, etc., involving a wide range of specialties while facing high technical difficulties. The design and manufacturing of new nuclear fuels are closely correlated, requiring design-guided process and process-feedback design with multidisciplinary joint efforts and close cooperation among various processes.

(5) Facilitated by enabling system is required. To ensure that human resources, equipment, materials, schedule, quality, safety, security and confidentiality are under control in the development and production of nuclear fuels, in addition to design and manufacturing, new nuclear fuel R&D also needs the support of various enabling systems. The enabling process in SE allows for managing lifecycle models, infrastructure, project portfolio, human resources, quality and knowledge, and enabling systems must be considered in tandem with the project itself so as to provide the required services in a timely manner.

3.2 SE practices in CNNFC

CNNFC has established a relatively complete management system for R&D projects and compiled a series of management outlines and rules. Authorized by the general manager of the company, the chief engineer is fully responsible for the management of R&D projects; the research undertaking units are responsible for the implementation of R&D projects, while all departments shall be liable for the management of R&D projects according to the division of duties, to support, supervise and serve the progressing of R&D projects. The R&D of new nuclear fuels go through the process of issuing R&D tasks, establishing a research team, implementing the R&D tasks, acceptance and evaluation of tasks, etc. During the R&D process, the enabling systems, like infrastructure, human resources, quality management and knowledge management, play a good supporting role in R&D projects. The project leader and all departments of the company will supervise and inspect the R&D project comprehensively, to find existing problems and eliminate serious mistakes that may affect the overall progress.

Since CNNC launched the initiative of "Pushing Systems Engineering for Strategy Implementation", CNNFC has taken an active response upon introducing systems science and the concepts into production, scientific research, engineering construction in order to reinforce its independent innovation and master key technologies. Here, two cases are discussed to demonstrate the SE features and practices in the R&D of new nuclear fuels in CNNFC.

(1) Case 1: R&D of medical cobalt adjuster rod assemblies

Gamma knife is the mainstream means of tumor radiation therapy, and currently, cobalt-60 isotope is mainly adopted as the gamma radiation source. In 2016, China National Nuclear Corporation (CNNC) approved the "medical cobalt-60 radioactive source development" project (*project approval*), in which the industrial production technology of medical cobalt-60 radioactive source was organized and implemented by China Isotope & Radiation Corporation. The assembly design was undertaken by Shanghai Nuclear Engineering Research & Design Institute (*design*), and the specific research tasks were undertaken by Chengdu Gaotong Isotope Co., Ltd., Qinshan Third Nuclear Power Co., Ltd. (*irradiation testing*, *operation*), and CNNFC (*R&D*, *production*), etc. The research goal of CNNFC is to launch the research on the production and testing technology of medical cobalt adjuster, master the component preparation process and testing method, and develop the ability of mass production and testing, by making use of the technical advantage of industrial cobalt adjuster rod assemblies, and aiming at the market demand for medical cobalt-60. This project fully reflects the life cycle stages of new nuclear fuel R&D and SE characteristics.

CNNFC has completed the R&D and produced five assemblies of medical cobalt adjuster rods, with controllable quality in the production process and all measurements of effectiveness verified, which were successfully irradiated for two years since early 2017. In April 2019, the first independent batch of domestic medical cobalt-60 was produced in Qinshan Nuclear Power Plant, and by the end of 2020, it had already been applied in domestic gamma knife. So far, CNNC's annual capacity of cobalt-60 can basically meet the domestic market demand. According to some analysis, driven by the rapid economic and medical development of developing countries represented by China and India, the global market demand for gamma radiation sources continues to rise, reaching $410 million in 2021 and expected to reach $490 million by 2025, and it is foreseeable that the successful development of medical cobalt adjuster component will also bring considerable economic benefits.

(2) Case 2: R&D of a mobile nuclear reactor

Mobile nuclear reactor technology belongs to microreactor technology, which is intended for the islet power supply in special environments like islands, plateaus, and polar regions, or in case of major disasters. With strong national defense and civil significance, mobile nuclear reactor technology has become a hot research spot of the nuclear industry worldwide. CNNFC is now taking an active part in the R&D of mobile nuclear reactors.

Here a certain mobile nuclear reactor R&D project is taken as an example. The project divides the R&D of a mobile nuclear reactor into key technologies as the overall system design technology, heat pipe reactor, energy conversion system, nuclear fuel and shielding materials, with four research topics (see Figure 2). The coupling of these four key research topics reflects the complex interface relationship of the mobile nuclear reactor system. CNNFC undertakes the research on advanced nuclear fuel and shielding material technology, expecting to master the key parameters and characteristics to support the reactor and platform design. The R&D process of dispersion fuel is further divided into stages of fuel element design, fuel element production process research, and the test and characterization of key parameters. The stages are progressed in iterations. During the design of nuclear fuel and shielding materials, the requirements of investors, designers, manufacturing plants, end users, operators, maintainers and other stakeholders are fully taken into consideration.

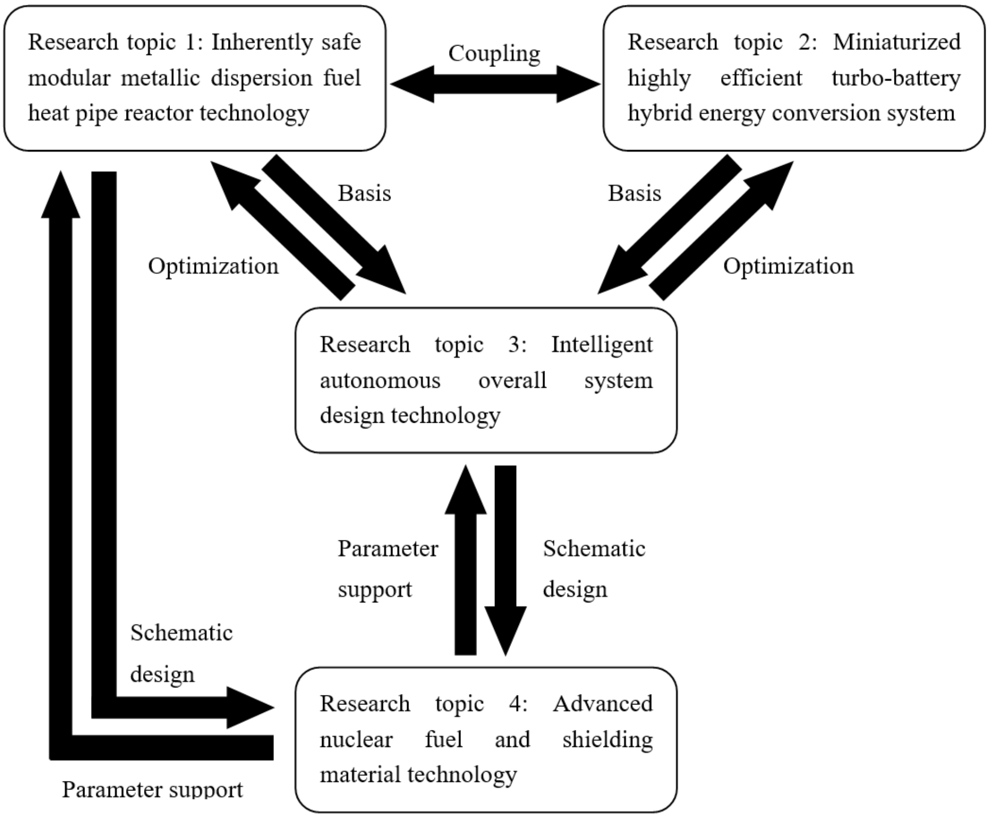

Fig.2 Research topics and their relationship in a mobile nuclear reactor R&D project

4 Proposals for accelerating the R&D of new nuclear fuels by deploying SE

For the needs of accelerating the R&D of new nuclear fuel, it is proposed to enhance SE in the following aspects:

(1) Adhering to systems science. The life cycle model of new nuclear fuel R&D should be improved, meaning from the very beginning of business and task analysis to the later operation, maintenance and decommissioning, technical processes should be carried out drawing on the SE Vee model, and verification and validation should be conducted well with good technical management processes, and project enablement processes, agreement processes and tailoring processes of the organization.

(2) Making good use of SE engineers.SE is an emerging practical discipline, and its smooth development cannot be reached without talents with corresponding knowledge and skills. The role of systems engineers with professional knowledge and management experience should be well played, and corresponding positions should be set up with related responsibilities assigned in the project to guarantee the time and conditions for carrying out SE.

(3) Introducing SE tools. With the development of science and technology, the increase of knowledge, the deepening of disciplinary crossover and the progress of information technology, SE approaches have been transformed to MBSE. Therefore, software tools required to carry out MBSE should be introduced to support the hardware conditions required for MBSE, and to improve informatization and management.

(4) Exploring SE characteristics. The above analysis and suggestions are based on existing practices; however, these are still far from understanding the rules and features of new nuclear fuel R&D in an accurate way. As a result, it is recommended to select a part of scientific research and engineering projects to carry out pilot SE projects and fully apply SE approaches for management, to accumulate experience in SE work, tailor SE processes, and thus establish SE approaches which are truly applicable to nuclear industry and nuclear fuel R&D.

5 Conclusion

A project for the R&D of new nuclear fuels is a system with the characteristics of systems. SE can be applied in nuclear industry, including the R&D of new nuclear fuels. By taking an active response upon introducing systems science and the concepts into production, scientific research, engineering construction, independent innovation can be reinforced and key technologies can be mastered. Thus, it is proposed that in order to accelerate the R&D of new nuclear fuels in nuclear fuel manufacturing plant, SE should be deployed and enhanced.

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