Systems Engineering and the Licensing of Small Modular Reactors

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T. Kulesa[1], K. Soderholm[2], P. Fechtelkotter[3]
[1] IBM, Philadelphia, PA (tkulesa@us.ibm.com)
[2] Fortum Power, Finland (Kristiina.Soderholm@fortum.com)
[3] IBM, Boston, MA (pfech@us.ibm.com)

Abstract

Both global warming and the need for dependable sources of energy continue to make nuclear power generation an appealing option. But a history of cost overruns, project delays, and environmental disaster has pushed the industry to innovate and design a more flexible, scalable, and safe source of nuclear energy - the small modular reactor.

Innovation in generation technology creates disruption in already complex licensing and regulatory processes. This paper discusses how the application of systems engineering and requirements management can help combat confusion, rework, and efficiency problems across the engineering and compliance life cycle.

The paper is based on the PhD Dissertation "Licensing Model Development for Small Modular Reactors (SMRs) - Focusing on Finnish Regulatory Framework"[1], approved in 2013.
The result of the study gives recommendations and tools to develop and optimize the licensing process for SMRs. The most important SMR-specific feature, in terms of licensing, is the modularity of the design. Here the modularity indicates multi-module SMR designs, which creates new challenges in the licensing process. Another feature impacting licensing feasibility is the plan to build many standardized power plants in series and use factory-fabricated modules to optimize the construction costs. SMR licensing challenges are under discussion in many international forums, such as World Nuclear Association Cooperation in Reactor Design Evaluation and Licensing Small Modular Reactor group (WNA CORDEL SMR) group and IAEA INPRO regulators' forum.
This paper also presents an application of the new licensing process using Systems Engineering, Requirements Management, and Project Management practices and tools.

1. Introduction

The small modular reactor is an attractive option for the future of the nuclear industry for many reasons including modularity, scalability, cost, and safety. In recent years, nuclear projects have realized many challenges, partly because of increased regulatory burdens but also because customized designs require customized compliance and licensing. These licensing processes are gaining an increase in attention with the latest new build nuclear projects around the world. Licensing processes for new nuclear power plant units also have been under evaluation and development. The licensing process as well as tools and practices, such as Systems Engineering (SE) and Requirements Management (RM), are an important element of these discussions.

To achieve success in nuclear licensing, the licensing process, as well as practices and tools for managing the processes, requirements and the complex system of systems are important pieces. As SMRs gain interest and their anticipated time of commercial availability creeps closer, the licensing and regulatory concerns must be evaluated thoroughly to ensure a sustainable model into the future. SMRs have begun their licensing activities and they can be used as a first step towards international approval of a nuclear power plant, either SMR or traditional.

This paper examines the nuclear licensing processes and discusses tools providing transparency, efficiency, trust, and speed in the nuclear industry. This kind of wide overall view enables better licensing, improves the overall safety of the nuclear power plant and nuclear energy production, and can help drive down the overall cost of nuclear projects from design to production. The complex system of systems should be clearly understood using better engineering techniques to assure safe and uninterrupted nuclear energy into the future.

2. Licensing in the Nuclear Industry

2.1 SMR Licensing is Unique

Licensing as one of the key factors has also been evaluated by the World Nuclear Association WNA [2]. International organizations, such as International Atomic Energy Agency (IAEA) and WNA have noticed the need of focused discussion of SMR-specific features. The fact that SMRs are smaller and more simplified when compared to large Nuclear Power Plants (NPPs) that are the norm today should be utilized in order to be able to more easily overcome the licensing challenges. SMRs could provide a suitable arena to develop new licensing process, as well as practices and tools, which could be later utilized also in large NPPs.

SMR traits such as size and modularity should be utilized to more easily overcome licensing challenges. However, the licensing process needs focused development to suit modular designs, with modularity meaning the many reactor modules within one unit. The modular licensing aspect should be the focus point in each country's domestic SMR deployment, but even more important is the development in the international nuclear arena. In Europe, this situation is particularly pronounced, since the licensing processes and licensing requirements is country-specific or localized causing variations in the design and more effort on licensing in each deployment country separately. With SMRs this situation is an even greater challenge since there are plans to build SMRs as fleets, and therefore some parts of the licensing should be transferable from one county to another.

2.2 Licensing Processes Vary by Country

The licensing processes of the USA, Canada, the UK, France and Finland have been selected as examples to illustrate how much the process varies from one country to another. Each of the countries' respective licensing processes have unique features, but after evaluating the steps, it is evident there are similarities across the countries. The evaluation was based on current licensing processes that are developed for large NPPs needs [1]. The following table presents the comparable licensing steps in the studied countries: even if the comparison is not straightforward some similarities can be found (see Table 1).

	Pre-Licensing	Political	Licensing on new nuclear facilities			Hold points
FINLAND	Environmental Impact Assessment (EIA)	Decision in Principle	Construction License		Operating License	
USA	Early Site Permit Standard Design Certification		Combined Construction and Operating License (COL)			ITAAC
CANADA	Vendor Design Review		License to Prepare Site Environmental Assessment	License to Construct	License to Operate	
FRANCE	ASN opinion on safety options	Multiyear investment plan	The authorization decree for NPP creation		License for the commissioning of the installation	
UK	Generic Design Assessment (GDA)		Nuclear Site License (Environmental, Safety and Security review processes)			Established hold points

Table 1: Nuclear licensing processes in different countries [3]

One notable feature is that the pre-licensing activities are getting more attention in countries where new Nuclear Power Plants (NPP's) are licensed. Pre-licensing is not a new feature; however the scope has been extended in recent years, especially in regards to new technology (SMRs) and more complex (possibly digital) instrumentation and controls (I&C).

2.3 Review of Licensing in Adjacent Complex Industries

Features from adjacent complex industries are important to discuss in order to identify practices that could be leveraged for SMR development and licensing. Aviation licensing practices have been included in nuclear licensing discussions e.g. in the WNA report "Aviation Licensing and Lifetime Management – What Can Nuclear Learn?" [4]. However, the aviation industry has even more in common with SMR licensing, than with large NPP licensing, because of the modular design of SMRs.

A distinctive feature in the aviation industry is the high degree of trust between the USA, Europe, and a few other countries. Adopting a higher degree of trust is possible, however the development of more harmonized processes are required. Currently, the processes cannot easily transfer parts from one country to another due to the different scopes of the licensing steps in different countries. If the licensing processes were harmonized to some point, the countries and regulatory bodies could then recognize and even accept licensing conclusions from other licensing jurisdictions. It is recognized that this needs to be done by recognizing a country's sovereign right to perform an independent licensing review. Some initial steps towards this have been taken in, for example, the Multinational Design Evaluation Programme (MDEP) framework, in which the UK, Finland, and France have shared their high level assessments of the same design.

Harmonization of European and international standards has been seen in the aviation industry. The international harmonization efforts of the nuclear energy area are also in the focus point of many international organizations, such as the IAEA and Western European Nuclear Regulators Association (WENRA). The nuclear licensing process has been studied in the European Reactor Design Acceptance (ERDA) working group within the European Nuclear Energy Forum (ENEF) (under European Commission), which is developing parts of the licensing process in a more harmonized direction. The aviation industry has already reached standardized requirements between Europe, the USA, and some other countries. The actual aviation licensing process in different countries does not play that big a role in licensing, even if the liability for licensing remains within the countries because of the international approval of a certain country's certification of an aircraft. This kind of development could help streamline licensing in the nuclear industry.

Another lesson to be learned from the aviation industry concentrates on requirements-based licensing. The licensing requirements are split into two separate parts. This approach is also used in certain international requirements in the nuclear field. As an example of a two part licensing requirements in Europe, can be mentioned the European Commission safety objectives, while every member country sets their own safety requirements.

3. Complex Systems and the Application of Systems Engineering

As shown in Figure 1, a nuclear plant faces extreme challenges managing both highly-coupled and non-linear sub-systems/systems interactions. Industries with similar, but slightly less challenging, complexity profiles include aircraft, space, defence, and chemical; however there is a gap between them and the nuclear industry in the application of technology and the discipline surrounding systems engineering. The Aerospace and Defence industry has been leveraging systems engineering principles for more than 20 years; similarly, space missions and unmanned vehicles also utilize the systems engineering discipline to ensure safety, security, and accuracy from the mission statement to the lowest level subsystem requirements.

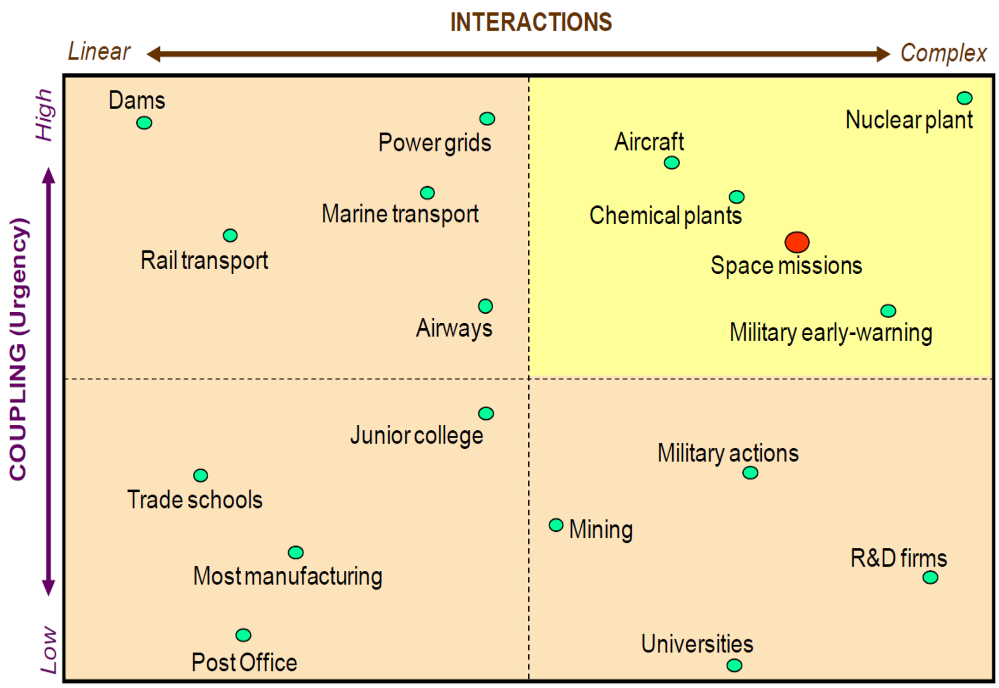

Figure 9. Systems that must manage complex interactions and high coupling are more prone to accidents. Space missions are among these high-risk systems.

Figure 1: Complexity of nuclear power plant as system of systems [1]

3.1 An Optimized System using Requirements

Over the last two decades, aerospace and defense (A&D) and oil and gas plant systems have seen significant benefits from looking at a space probe, aircraft or a drilling platform as an entire system that is composed of multiple sub-systems consisting of mechanical, electrical, software, and human factors elements. Each of the sub-systems (one could think of them as black boxes) meets a set of well-defined requirements. The requirements not only define what the system should do and how well it should do it, but they also capture requirements for compliance to safety standards and governmental regulations. There must also be a well-defined set of interfaces and well-maintained linkages between each of the sub-systems. As a result, the system can be optimized holistically but the impact of changes in individual components or sub-systems can be made visible. Extending this concept to Nuclear Power Plant Systems (NPSS), the "system" could be a complex, expensive asset such as the entire nuclear island, analogous to an offshore platform, a Liquefied Natural Gas (LNG) plant or a pipeline.

4. Systems Engineering Approach for the Nuclear Industry

Energy companies are increasingly leveraging the systems and software engineering best practices developed in adjacent highly-regulated, fail-safe industries such as aerospace, defense, automotive, transportation, and medical to aid in optimally balancing regulations, licensing, safety and increased complexity.

Technology can be used to better connect, store content and collaborate within an ecosystem of EPCMs (engineering, procurement, construction, management firms), regulators, operators and equipment manufacturers. As other fail safe industries have evolved from hard-copy documents to electronic documents to integrated models using interdisciplinary engineering principles, they have reduced the traditional separation between organizations and domains and demonstrate how to better leverage software, analytics, open standards and a digital savvy workforce.

As previously stated, international deployment of nuclear projects is gaining traction, yet speed and efficiency in the process is held back by a lack of a common terminology. Silos across the disciplines of design, material, I&C, safety, etc coupled with silos across the vast multi-party ecosystem involved in the nuclear power projects further highlights the need for more commonality across the value chain. In order to be safe, competitive and efficient the industry must adopt transparency across processes; trust, speed, and agility; international harmonization of licensing requirements; and more standardization of designs.

The application of systems engineering principles and supporting technology can help the industry cope with increased complexity and the need to meet stricter regulatory standards while improving efficiency and reducing costs. The solution helps solve these challenges by enabling better traceability, impact analysis, change management, visibility, prioritization, and collaboration across the ecosystem of government regulators, O/O's (owner / operators), suppliers, EPCM's, etc.

The lack of integration and visibility between processes, tools and data across disparate, disjointed disciplines and organizations makes it nearly impossible to trace and identify the total impact of changes in critical systems and software. The introduction of technology, primarily personal productivity tools, improves each individual's output but without strong governance and an integrated platform, the technology can make it harder to collaborate and synchronize across the distributed ecosystem. A seemingly insignificant change in one small area of the plant or design may have a material effect on the O/O's overall safety and compliance posture and risk.

4.1 Approach and Solution: Requirements Driven Engineering

Key elements to making the systems engineering approach successful is the application of Requirements Driven Engineering (RDE) and Model Driven Development (MDD) combined with a governance framework that captures and manages the process of design, development and production. This paper will only discuss RDE.

RDE is a means to create and manage requirements in a structured manner so that they are unambiguous, atomic, and testable. Good requirements detail what something should do but defer decisions about how it should be accomplished until the design phase. In the nuclear industry, RDE is growing in adoption in the design and licensing process as depicted in Figure 2, which highlights the common thread of requirements. This figure separates the design process into 3 phases, starting with plant design (on the top of the figure), and following by systems design and then component design. These phases can also be called conceptual design, basic design and detailed design, terminology varies widely. Each component plays an integral role in specifying the requirements and criteria seen in the nuclear licensing process flow. The criteria or requirements are recursively specified, tested, altered, modified, approved and audited through the entire life cycle

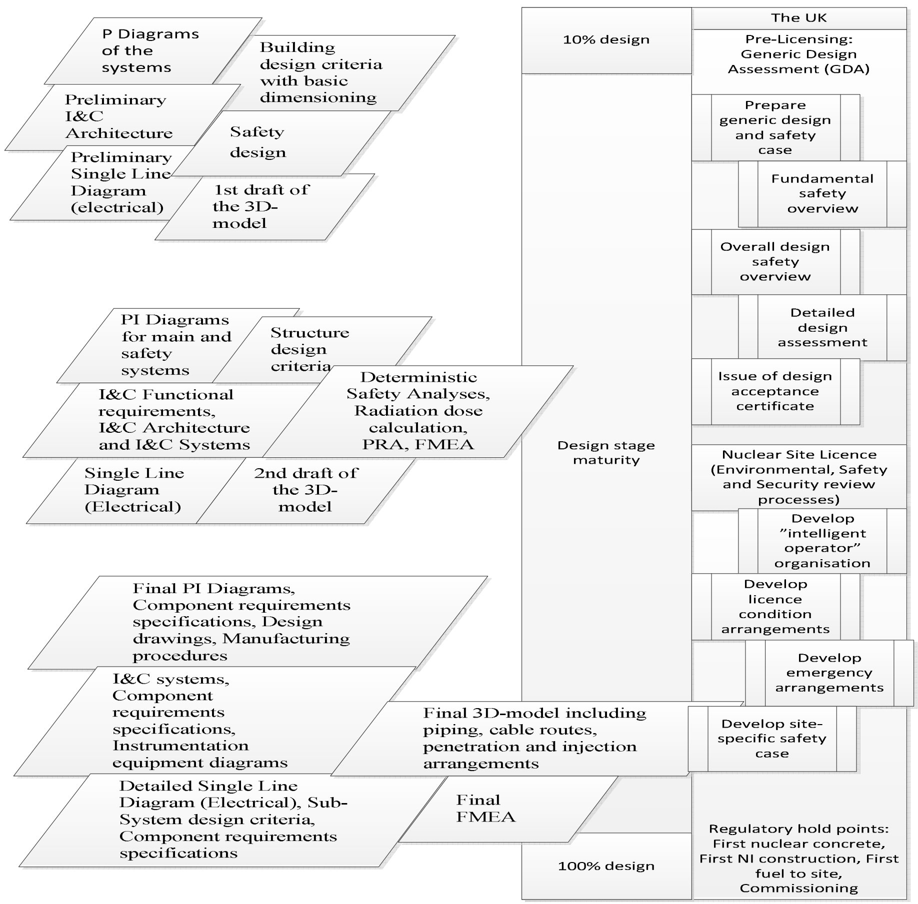

Figure 2: The nuclear licensing process has inter-linked requirements as a common thread, as do other safety-critical industries [5]

Each layer of requirements is developed, agreed upon and verified before they are passed onto the next level, to which they are traced/linked. As the requirements evolve through this process, verification tests are developed in parallel. These are used to verify the products, systems, and/or solutions developed are compliant with the requirements.

Typically much of the specification, design, technical, and regulatory requirements information exist in unstructured documents, usually extremely long and complex, stored in a document repository or multiple repositories. In most cases the information is hard to find, there is little or no configuration management of the documents and there is little or no traceability among the information elements (e.g. regulatory or compliance requirements) embedded in the documents.

The advantage of decomposing these typically long and complex documents into sets of requirements in a tool is that the information elements in the documents can be managed in a structured manner and can be related together using formal linking mechanisms. The linking is critical to creating and managing high-quality, robust and consistent requirements as it allows analysis of the impact of a change to a design or specification. This analysis can be carried out to determine the true cost of the change, and influence on safety, before it is accepted. This analysis is extremely difficult to perform if documents are not related at the correct level of detail (as is the case in document management systems) as project members do not have a holistic view of how a proposed change's impact cascades across the entire project. Robust linking and "advanced management tools and methods" are also critical in the licensing process [5].

Many organizations already are utilizing the RM approach to support nuclear design and licensing activities and more rigor is being developed for the future. There are many lessons and opportunities in RM that can be applied now.

4.2 Applying the Processes and Tools to Licensing

Nuclear licensing, both in international and national regimes, use established practices and tools to handle the complexity of licensing and design actions. Technical processes for management systems usually include at least: Design Management (DM), Configuration Management (CM), Change Management, Requirements Management (RM) and Quality Management (QM). However, these processes vary from one country to another, as well as from one company to another.

Harmonization across the ecosystem could provide a common platform to start. One solution for this variation of terminology is the use of an established method, such as Systems Engineering (SE) and then building a co-evolutionary approach for the licensing projects adapting SE principles, Requirements Management (RM) practices, and including Project Management (PM) tools. The presented theory is a simple and comprehensible model combining various levels of licensing aspects. The novelty of the RM approach in the nuclear industry is the determined categorization of the licensing requirements and comprehensive follow-up of each requirement during the whole lifecycle of the plant.

Presented approaches are methods that are widely used in other industries. These practices could be utilized in the nuclear industry, especially for licensing activities. One of the main benefits of using these methods, especially SE, would be better communication between interest groups. Validation and verification is important in licensing, compliance and regulatory approvals, and the overall process and traceability could be carried out through RM and SE processes.

SE and RM have been introduced as a practical tool to manage the licensing of a very complex ensemble. On top of these methods, the Project Management (PM) should be combined in the process, to enable successful licensing project. It has been one of the lessons learned from current licensing activities in the Finnish nuclear industry that the management of licensing requirements is one of the key components for successful licensing.

Effort has been put into connecting the SE processes and project phases with the licensing process steps. There are good standards available in SE and PM fields, so the following standards have been chosen for this purpose: ISO/IES 15288 [6], ISO 21500 [7] and PMBOK [8]. Fig. 3 and 4 present the interconnection of the processes, using the UK and the US licensing processes as a basis.

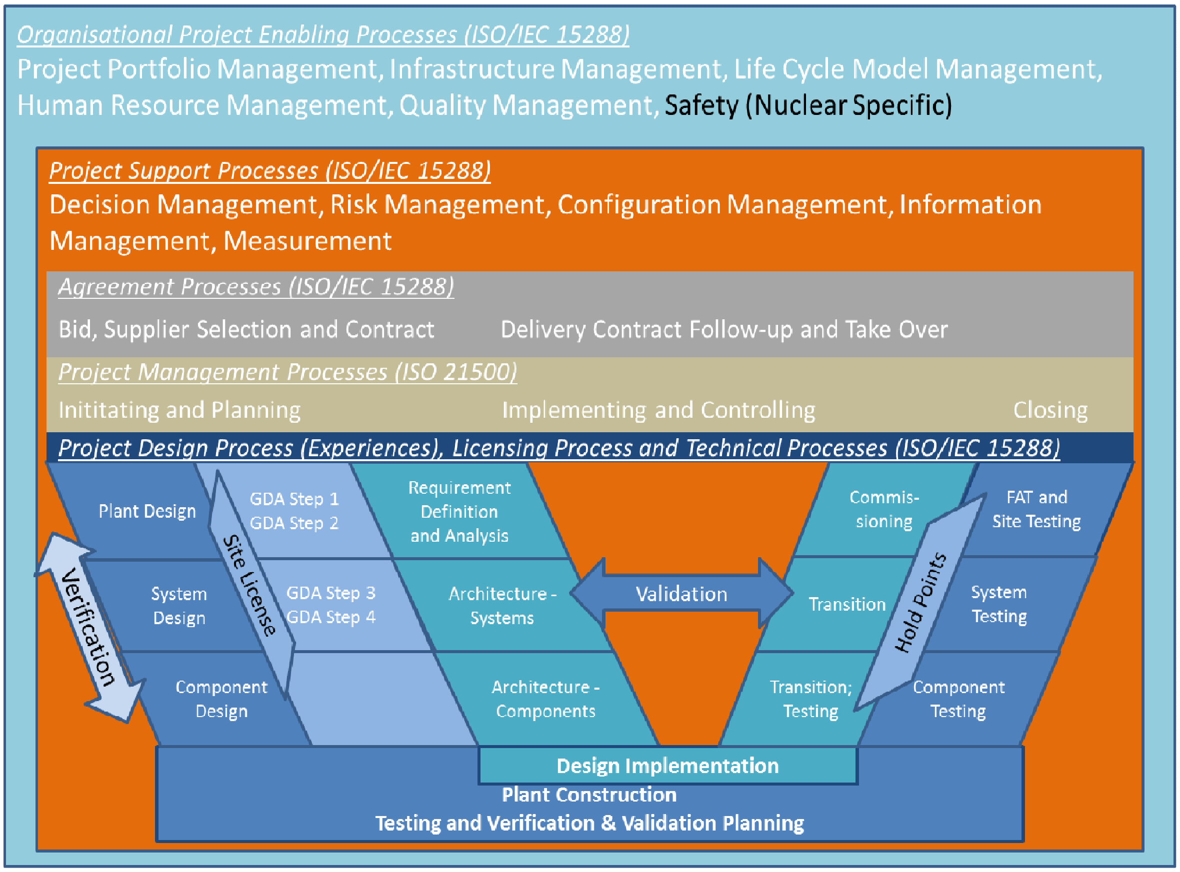

Figure 3 Licensing model for the UK licensing using SE and PM practices [5]

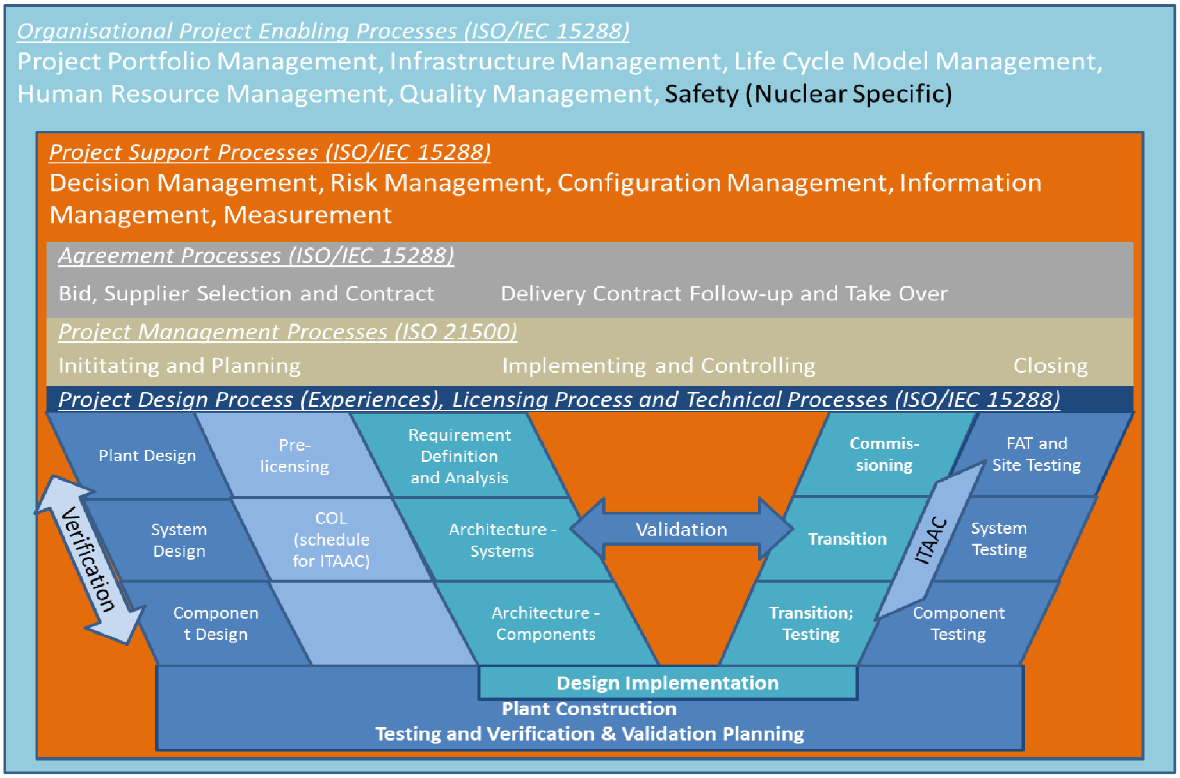

Figure 4: Licensing model for the US licensing using SE and PM practices [5]

Figures 3 and 4 are divided into areas (indicated in different colors), starting with large entities, such as Organizational Project Enabling Processes (with light blue color). The next layer is Project Support Processes (with orange color), moving to a smaller scale and to a specific project with PM Processes (with gray and brown colors). The V-model presents the Project Design Process (dark blue), Licensing Process (light blue), and Technical Processes, such as RM Process (turquoise). The UK and US licensing processes are used in this example. Therefore for the UK licensing, the GDA steps 1-4 have been introduced as pre-licensing activities, as well as site licensing phase as the actual licensing step. In the US licensing, the Design Certification and Site Permit, as the pre-licensing activities, and Combined Construction and Operating license as the actual licensing step.

These two licensing processes have many similar features; however the approach is very different. In the US the licensing is based on very prescriptive approach with detailed NRC requirements and defined set of codes and standards. In the UK the ONR sets only high level requirements for the licensee to present the safety of the design through "safety case". The codes and standards play an important role, but the approach is overall very different from the US approach.

This difference brings up the need of RM process in both licensing activities; however the RM process and tools need to be applied for each country's specific licensing features. This way the RM process and tools can be utilized effectively to help the licensing activities.

One example of the RM development for licensing purposes is an ongoing cooperation project between regulators and licensees in Finland, in which the regulatory requirements are addressed and categorized in terms of common selected features (attributes in RM database). As a result of the project the common database will be created for all the shareholders to use. From this common database, each project and organization can further develop more detailed database for their own purposes. However, the common basis for all the actors as well as clarity to the regulatory framework can be delivered through this approach.

As an example of the V&V process in I&C is presented in Fig 6. I&C discipline has a longer experience of the SE approach in the nuclear field, than other disciplines.

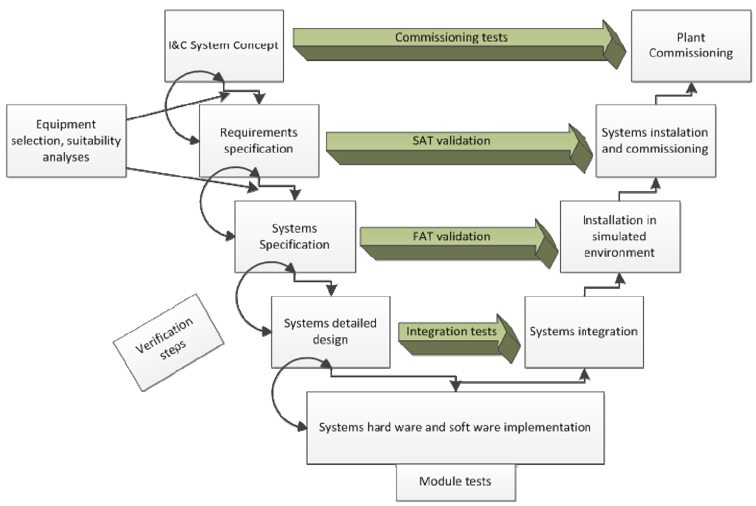

Figure 5: Example of V&V in nuclear I&C [1]

5. Conclusion

We need to rethink the role of nuclear energy within the clean energy power generation portfolio and enable competitive nuclear power production in the current and future power production system.

Nuclear licensing process and practices in different regulatory frameworks are evaluated and discussed in this paper. The research indicates benefits of certain type of licensing approach to improve the efficiency on nuclear licensing, and therefore nuclear energy production. One of the main benefits of the presented Systems Engineering (SE) and Requirement Management (RM) approach can be utilized in first movers, such as SMR developers and SMR operators.

The complex and wide set of licensing requirements needs advanced management tools and methods to be well organized and taken care of systematically. One suggestion for further development in the international nuclear arena could be the development of a RM database containing selected international guides. Perhaps, IAEA guides and relevant standards, such as certain ASME (American Society of Mechanical Engineering) standards, could build up an effective tool to support the licensing activities.

This kind of activity would also support harmonization of the requirements internationally, and therefore standardization of the nuclear power plant designs (both large and small nuclear reactors).

Software and Systems Engineering tools can help to reinvent the nuclear industry's approach by allowing the transparency in licensing as well as designing, which empower trust; by providing an umbrella and common platform for a large and complex ecosystem, which can create agility; by enabling more efficient working processes, which will promote competitiveness; and by providing a common language and standardized terminology, promoting better discussions and deeper understanding.

The urgent need of process development is not only a licensing efficiency issue, but an overall safety issue as well. Nuclear power plant safety is not only the traditional reactor safety, but also organizational, operational processes, safety culture and many other factors build up the system of systems that is the basis of safety

6. References

[1] Söderholm, K, "Licensing Model Development for Small Modular Reactors (SMRs) - Focusing on Finnsh Regulatory Framework", Thesis for degree of Doctor of Science (Technology), 2013 ISBN 978-952-265-451-9, ISBN 978-952-265-452-6 (PDF)

[2] Licensing & Permitting Task Force of the World Nuclear Association, 2012, "Licensing and Project Development of New Nuclear Plants", WNA Report: A Report by the World Nuclear Association's Licensing & Permitting Task Force, Report No.: 2013/002

[3] K. Söderholm, "Challenges on SMR Licensing Practices", *AECL Nuclear Review,* Volume 1, Number 2, 2012, Special Issue on Small Reactors, Available at: www.aecl.ca/Assets/Nuclear_Review/ANR_1-2_ENG.pdf

[4] The World Nuclear Association's Working Group on Cooperation in Reactor Design Evaluation and Licensing (CORDEL), "Aviation Licensing and Lifetime Management – What Can Nuclear Learn?" *WNA Report*, 2013 Report No: 2013/001

[5] Soderholm, K. Amaba, B. and Lestinen, V. "Licensing Process Development for SMRs – European Perspective". Proceedings of ASME 2014 Small Modular Reactor Symposium, Washington D.C., April 15-17, 2014.

[6] ISO and IEC, 2008, "Systems and software engineering - System life cycle processes", International Organisation for Standardisation and International Electrotechnical Commission, ISO/IEC 15288

[7] ISO, 2012, "Guidance on project Management", International Organisation for Standardisation, ISO 21500

[8] ANSI/PMI, 2008, "A Guide to the Project Management Body of Knowledge", PMBOK Guide, Fourth Edition, ANSI/PMI 99-001-2008, ISBN: 978-1-933890-51-7