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Integrating Safety, Operations, Security, and Safeguards (ISOSS) into the Design of Small Modular Reactors: A Handbook

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Integrating Safety, Operations, Security, and Safeguards into the Design of Small Modular Reactors: A Handbook

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Abstract

The existing regulatory environment for nuclear reactors impacts both the facility design and the cost of operations once the facility is built. Delaying the consideration of regulatory requirements until late in the facility design - or worse, until after construction has begun - can result in costly retrofitting as well as increased operational costs to fulfill safety, security, safeguards, and emergency readiness requirements. Considering the scale and scope, as well as the latest design trends in the next generation of nuclear facilities, there is an opportunity to evaluate the regulatory requirements and optimize the design process for Small Modular Reactors (SMRs), as compared to current Light Water Reactors (LWRs).

To this end, Sandia has embarked on an initiative to evaluate the interactions of regulations and operations as an approach to optimizing the design of SMR facilities, supporting operational efficiencies, as well as regulatory requirements. The early stages of this initiative consider two focus areas.

The first focus area, reported by LaChance, et al. (2007), identifies the regulatory requirements established for the current fleet of LWR facilities regarding Safety, Security, Operations, Safeguards, and Emergency Planning, and evaluates the technical bases for these requirements.

The second focus area, developed in this report, documents the foundations for an innovative approach that supports a design framework for SMR facilities that incorporates the regulatory environment, as well as the continued operation of the facility, into the early design stages, eliminating the need for costly retrofitting and additional operating personnel to fulfill regulatory requirements. The work considers a technique known as Integrated Safety, Operations, Security and Safeguards (ISOSS) (Darby, et al., 2007). In coordination with the best practices of industrial operations, the goal of this effort is to develop a design framework that outlines how ISOSS requirements can be incorporated into the pre-conceptual through early facility design stages, seeking a cost-effective design that meets both operational efficiencies and the regulatory environment.

The larger scope of the project, i.e., in future stages, includes the identification of potentially conflicting requirements identified by the ISOSS framework, including an analysis of how regulatory requirements may be changed to account for the intrinsic features of SMRs.

ACKNOWLEDGMENTS

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CONTENTS

FIGURES

TABLES

NOMENCLATURE

BIM	Building Information Modeling
CE	Concurrent Engineering
CFR	Code of Federal Regulations
DBT	Design Basis Threat
DOE	Department of Energy
EOF	Emergency Operations Facility
EPA	Environmental Protection Agency
EPZ	Emergency Protection Zone
ERDS	Emergency Response Data System
FLCM	Facility Lifecycle Management
FMJ	Facility Management Journal
GDC	General Design Criteria
GSA	General Service Administration
HFE	Human Factors Engineering
IAEA	International Atomic Energy Agency
ISG	Interim Staff Guidance
ISOSS	Integrated Safety, Operations, Security and Safeguards
LCA	Life Cycle Acquisition
LCC	Life Cycle Cost
LCCA	Life-Cycle Cost Analysis
LSC	Life Support Cost
LWR	Light Water Reactor
MC&A	Material Control and Accountability
MCR	Main Control Room
MLDT	Mean Logistics Downtime
MTW	Mean Time Waiting
MTTF	Mean Time to Failures
MTTR	Mean Time to Repair
MWe	Megawatts electric
NPP	Nuclear Power Plan
NRC	US Nuclear Regulatory Commission
NUREG	NRC technical report designation
PAG	Protective Action Guideline
PMO	Project Management Organization
PWR	pressurized water reactor
RG	Regulatory Guides
SME	Subject Matter Expert
SMR	Small Modular Reactor
SNM	Special Nuclear Material
SOSS	Safety, Operations, Security and Safeguards
SRP	Standard Review Plan
SSS	Safety, Security and Safeguards

1. Background

1.1. Traditional Reactors and Small Modular Reactors

The International Atomic Energy Agency (IAEA) defines reactors based on their energy output: a "small" reactor generates less than 300 MWe, a "medium" reactor generates between 300 and 700 MWe, and a "large" reactor has a power output greater than 700 MWe. Although these definitions are based on energy output, small and medium reactors are also designed to be physically small (Ingersoll, 2009), as compared to the current designs for Light Water Reactors.

For years, the general perspective regarding power generating plants (including gas, diesel and nuclear versions) has been that increasing the scale of electric generating units leads to declining energy generating costs (Goldsmith, 2011). However, factors such as changes in the technologies, rising investment costs, and the political issues associated with siting large units have led to increased commercial interest in smaller, modular designs, which can circumvent these obstacles and be cost-efficient from the manufacturing phase through the operational phase. Furthermore, the increasing demand for electricity, the excellent record of the existing nuclear reactors, the concern for fossil fuels, and the awareness of the impact of energy supply on national security (Ingersoll, 2009) have resulted in the United States renewing efforts to further develop nuclear technologies. To that end, small modular reactors are poised to be a feasible alternative for energy generation due to the many advantages they present.

Small modular reactors (SMR) are nuclear generating units that provide about one-tenth to one-fourth the power of a full-sized reactor, but that require only a fraction of the cost to develop and bring online (Atkinson, 2010). The size and the lower power output that characterize SMRs make them an attractive alternative for energy generation in a variety of scenarios, such as military installations (Ingersoll, 2009), developing countries (Juhn, 2002; Peterson, 2010), and utility companies (Atkinson, 2010) with small grid sizes – such as islands and remote locations (Juhn, 2002; Ingersoll, 2009). Furthermore, SMRs have a multitude of uses besides the obvious (power production) (Ingersoll, 2009; Juhn, 2002; Atkinson, 2010), including process heat (Ingersoll, 2009), district heating (Juhn, 2002; Ingersoll, 2009), sea water desalination and purification (Juhn, 2002; Ingersoll, 2009; Peterson, 2010), repowering already existing coal or nuclear sites (Atkinson, 2010), advanced oil recovery, and energy conversion, such as coal to liquids (Ingersoll, 2009) and hydrogen production (Ingersoll, 2009).

SMR designs fall into four general categories of reactors: light water-cooled, high temperature gas-cooled, molten-salt cooled, and liquid metal-cooled (LaChance, et al., 2007).

1.2. Benefits of SMRs

There are several considerations that make the manufacturing and operation of small reactors beneficial on multiple fronts. The intrinsic characteristics of SMRs result in benefits in the areas of plant safety, fabrication, operations, and economics (Ingersoll, 2009) as discussed below.

1.2.1. Fabrication

Modular reactors can be manufactured quickly, making the reduced construction time one of their more attractive features. Mass production of equipment and the modular construction of SMRs make them competitive (Juhn, 2002). A small reactor can be operational in about half the time it takes to build a traditional reactor (Atkinson, 2010).

One of the innovations that make this time reduction possible is modular construction. Because small reactors feature much smaller parts than their larger counterparts, the reduction in size allows for reactor parts to be standardized and manufactured under more controlled factory conditions (Ingersoll, 2009), and for the reactor to be partially assembled in a manufacturing setting (which improves the standardization and quality assurance of parts). The partially assembled reactor can then be transported to the site for final assembly (Atkinson, 2010; Peterson 2010).

1.2.2. Plant Safety, Security and Safeguards

The safety and security of a nuclear facility transcend all considerations of size, location, and intended use. The current status of SMRs provides an opportunity for safety and security considerations to be intrinsically embedded in the design of the reactor, eliminating the need for the expensive retrofitting that often occurs on the larger LWR models. According to Ingersoll (2009), SMRs can enhance plant safety beyond that of the existing larger facilities, considering "…the reduced inventory of radionuclides […], the potential to eliminate design features that introduce accident vulnerabilities, and the opportunities to passively respond to unexpected transients."

Some features that are intrinsic to SMRs and that improve safety and security by design include:

- a much simpler design that uses fewer moving parts, reducing variables of failure (Atkinson, 2010),
- a much smaller nuclear reaction, which generates less heat (Atkinson, 2010),
- the elimination of large coolant pipes (Ingersoll, 2009), and
- a fully passive, natural-convection air ventilation that provides removal of decay heat (Ingersoll,2009).

SMRs also facilitate the implementation of innovative safeguards and verification methods, including both institutional and technical barriers. For example, SMRs may be designed to go for long periods of time without refueling, although the iPWR-type designs may have refueling cycles similar to existing large LWRs.

The interval is estimated to be between 8 and 30 years (Juhn, 2002), and possibly even as long as 100 years (Atkinson, 2010). Some models being considered do not need any on-site refueling at all (Juhn, 2002), which effectively eliminates the possibility of fissile material proliferation. These features also contribute to minimizing the waste generated.

Additionally, the small size provides the option of placing the site below ground level, improving the reactor's resistance to external sabotage events (Ingersoll, 2009; Peterson, 2010). At a minimum, the safety systems and reactor containment can be located underground, making them easier to protect (Atkinson, 2010).

1.2.3. Operations and Economics

The small size of SMRs allows for a variety of flexibilities that have not been historically possible for nuclear technology, including siting, load demands, the stability of the grid, water usage, demand growth, plant economics, project cost, and economies of scale (Ingersoll, 2009), as well as dual use of electricity for energy generation and desalination (Juhn, 2002). Refueling intervals that range from 5 years to 30 years – and even longer – are very attractive for both facility operations and economics. Replacement of the fuel in such a reactor would happen less frequently than it does in the current fleet of nuclear reactors, thereby increasing the plant's availability (fraction of time during which the plant is actually generating electricity) for that period of time.

The nature of the technical requirements of SMRs also allows utilities and government entities to consider locations where it would be impossible or difficult to locate a large reactor. The lower requirement for cooling water allows for consideration of locations with limited water supplies (Atkinson, 2010). The smaller size and modular construction allow for locations that are more difficult to reach, because the semi-assembled parts can be transported via train, river barge, and truck (Ingersoll, 2009). Additionally, the smaller size makes it possible to consider locations that have a history of seismic activity, because the small design can incorporate seismic isolators, reducing the probability of seismically-induced damage (Ingersoll, 2009).

One important consideration for the viability of SMRs is the total project cost and the economies of scale that can be achieved. According to Ingersoll (2009), the total project cost for SMRs should be significantly less than that for large plants, which can enable potential customers to enter the market sooner than would be possible with a large LWR design. Considering economies of scale and a normalized cost of energy, SMRs are not economically feasible unless additional factors are considered, including factors that are independent of size (e.g., modularity, factory fabrication, site infrastructure, process learning), as well as factors that are unique to small plants (e.g., design simplification, plant compactness, economy of replication). The regulatory requirements that guide the licensing of both large and small reactors may have a significant impact on the economics of SMRs, making the project cost and economies of scale more representative of the benefits intrinsic in the design.

2. Regulatory Requirements for Nuclear Facilities

Despite the intrinsic differences between the traditional light-water reactor and the SMR, and taking into consideration the benefits that SMRs present in terms of the safety and security of the installation, the regulatory requirements applicable to light-water reactors remain consistent regardless of the design. Furthermore, the requirements imposed might, in some cases, present issues for the economics of the much smaller design, and may not be optimum for all issues involved in the design and operation of the plant, (e.g., a safety requirement might need a door open while security issues mandate that the same door be locked).

A single SMR design has yet to be approved and it is difficult to assess the impact that regulatory requirements may have on SMR design, economics, and operations. However, because policies and licensing requirements currently are geared toward large reactors (Atkinson, 2010), it is important to consider the regulations and the design in the early stages of SMR development to ensure that the requirements can be met without eliminating some of the benefits identified by the deliberately small design. Furthermore, there are new issues that are specific to SMRs in terms of fee payment, emergency planning, security, control rooms, operator staffing, etc. (Atkinson, 2010), that need to be addressed with regulators prior to any design approval.

Juhn (2002) documented the need for dialogue between designers and regulators to incorporate safety requirements at the conceptual design stage to avoid later delays in the licensing process. Atkinson (2010) stated that the regulator "… might need to review many of its rules and standards to determine … whether SMRs merit a different set of requirements."

2.1. A Review of Regulatory Requirements and Their Impact in SMR Design

A full review of current regulations was conducted as part of this project effort. The review of the regulations pertaining to Safety, Security, Operations, Safeguards, and Emergency Preparedness of nuclear facilities was aimed at understanding their applicability to SMR designs. The focus of this review was twofold: 1) to assess whether existing regulations established for traditional reactors are relevant to new reactor concepts, or should be amended, and 2) to identify the impact of these regulations in the design of SMRs (LaChance, et al., 2007). The results of this review are summarized below.

2.2. Safety

10 CFR 50, 10 CFR 20, and 10 CFR 100 provide the requirements for a power production reactor to be licensed by the Nuclear Regulatory Commission (NRC). These regulations are designed to mitigate the health and safety impacts of commercial power reactors on both the workers and the environment. 10 CFR 50 discusses the categories of the 55 items of the general design criteria (GDC). These categories are:

(1) General Requirements,
(2) Protection by Multiple Fission Product Barriers,
(3) Protection and Reactivity Control Functions,
(4) Fluid Systems,
(5) Reactor Containment, and
(6) Fuel and Radioactivity Control.

The current categories listed above could change for SMRs. Additional guidance documents containing safety requirements that apply to SMRs include:

- Standard Review Plan (SRP) in NUREG-0800,
- Regulatory Guides (RG),
- Interim Staff Guidance (ISG), and
- NUREG reports.

These documents are related to:

- The safe design of the plant,
- The design of structures, systems, and components to withstand external hazards, and
- The design of the reactor, reactor coolant system, engineered safety features, and the instrumentation and control systems.

RGs and ISGs are associated with LWRs. Some of the LWR requirements would not apply to SMRs, and additional requirements for the SMRs would need to be added. In addition, the NRC staff is establishing a set of Design-Specific Review Standards (DSRS) for different SMR designs. Each DSRS will address the unique characteristics of the design and its operation.

2.3. Security

The physical security regulations for NPPs are generally applicable to advanced SMRs, but strategies to maintain compliance and to reduce operating and staffing costs need to be considered. Operations differ for each NPP facility. The staff requirements to ensure protection are determined after considering the following: the material and facilities; maintenance of security programs (physical protection program, protective strategy, etc.); and normal daily security operations. One security-related target is to create an NRC-approved security plan that establishes the measures for maintaining the SMR’s performance, as well as its protection. Performance-based justification and additional research may be required to assess the efficacy of any new security measures. The expectation of the NRC is that security features will be integrated with the design. Security designs will also depend on the plant size, which may lead to a cost savings in the case of SMR security.

2.4. Operations

It could be argued that some current regulations may need to be adjusted to the reality of operating SMRs. In particular, modifications to regulations that prescribe the number, composition, or qualifications of licensed personnel required may be justified. Such is the case with regulation 10 CFR 50.54(m), which establishes the number of operators per unit and per main control room (MCR), but does not address a situation where three or more units are controlled from a single control room. Such multiple control scenarios could be the case for certain SMR designs.

The proposed NRC Strategy on Control Room Staffing suggests that NRC may evaluate exemptions from the MCR staffing regulations for advanced reactor designs. In addition, the regulations may not address the potential MCR configurations that may be proposed. For that reason, the NRC staff proposed both short- and long-term policies. The short-term policy covers the period in which there is no advanced SMR operating experience. The long-term policy covers the period when SMR operators have experience with SMRs. Each policy will be developed by revising the existing regulations and developing new regulations to provide SMR-specific control room staffing requirements.

A study of the issues relevant to the Proposed NRC Strategy on Control Room Staffing concluded that the new technologies associated with SMRs, as well as those incorporated into the design of new control rooms, will require further assessment to identify adequate SMR staffing instead of continuing to follow the current regulations in 10CFR 50.54 (m). The conclusions reached by this study are listed below:

2.4.1 When the advanced MCR designs reduced the crew size, performance was improved. The study recommended that the decision regarding optimal crew size take into consideration control design features such as function allocation, automation, integration, and plant-specific characteristics.

2.4.2 The study found that the NRC's staff guidance for reviewing an applicant's Human Factors Engineering (HFE) program is reasonable, but suggested that the NRC work with the industry to establish standardized and accepted levels of operator workload.

2.4.3 A released regulatory gap analysis proposes developing an exemption to the minimum licensed operator staffing requirements, based on a design-specific staffing plan that would be developed using the guidance of NUREG documents.

2.5. Safeguards

Several sections of the Code of Federal Regulations provide the nuclear material safeguard requirements to be met for NRC licensing, including the following:

- Material control - use of control and monitoring measures to prevent loss, or to detect loss within one hour of discovery (10 CFR 74),
- Material accounting - use of statistical and accounting measures to maintain knowledge of the quantities of special nuclear material (SNM) in each area of a facility (10 CFR 74),
- Possession and use of SNM and byproduct material (10 CFR 70).
- 10 CFR 70 establishes requirements to:

- Keep records and provide for inspections of all activities under the license;
- Report any changes in licensed material levels;
- Prepare and maintain a safeguards contingency plan;
- Submit emergency plans;
- Reporting requirements, including:
  - Any material loss or damage that could hinder the ability to properly control or account for material,
  - Unplanned contamination or criticality events
- Physical security for the requirements of 10 CFR 73 and 10 CFR 74.

10 CFR 74 establishes requirements for Material Control and Accountability (MC&A) of SNM at fixed sites:

- Documenting the transfer of SNM,
- General reporting and recordkeeping to any entity that possesses SNM in a quantity greater than one gram of contained 235U, 233U, or Pu,
- That each licensee report all loss, theft, attempted theft, or unauthorized production of SNM within one hour of occurrence,
- Material Balance and Nuclear Material Transaction Reports concerning all SNM received, produced, possessed, transferred, consumed, disposed, or lost,
- Perform independent tests on all material, no matter the location within the facility (including in-process), to ensure proper accounting.

SMRs will require licensing under these regulations, because the 10 CFR requirements are applicable to all nuclear facilities, including LWRs.

2.6. Emergency Readiness

Some emergency planning regulations, regulatory guides, and other guidance documents are fully applicable to SMRs, but exceptions may include the following: size of the emergency planning zone, notification times, shared facilities, collocation with other SMRs and other nuclear power reactors, number of staff positions, and circumstances requiring augmented staffing and/or shared staffing. The guidance presented below contains descriptions of how the regulation may apply to SMRs:

- NUREG-0654 provides the specific guidance for staffing requirements for nuclear power plant emergencies, specifying a minimum of 10 on-shift responders in four functional areas, and seven on-shift responders who perform response duties that may be performed by shift personnel in addition to their other assigned functions. Firefighting and site access control are staffed on a site-specific basis. This type of shared staff function will be particularly relevant for SMRs with multiple reactors and shared control rooms. In addition, NUREG-0654 specifies the required number of “augmenting responders” within 30 and 60 minute timeframes. For SMRs with passive safety features, the time required to augment the emergency staff will be relevant, and will depend upon the safety features and their impact on accident progression.

- Appendix E of 10 CFR 50 describes the Emergency Response Data System (ERDS), which is a direct, near-real-time electronic data link between the licensee's onsite computer system and the NRC that provides an automated transmission of a limited set of selected parameters. A parameter set appropriate for each type of SMR would need to be developed.
- NSIR/DPR-ISG-01 states that there have been several requests to the NRC to combine Emergency Operations Facilities (EOFs) for multiple plants within a state or in multiple states, where an EOF could serve multiple units or units with more than one type of reactor technology. This may apply to SMRs. EOF staff will need to be capable of understanding plant conditions for each type of reactor technology, particularly if the EOF for an SMR is co-located with different reactor technologies.
- Risk-significant emergency planning standards 1) classify any emergency event (defining an emergency action level), 2) notify emergency responders and offsite officials of a declared emergency (including alert and notification systems), 3) perform dose assessment, and 4) develop protective actions. All of these standards apply to SMRs.
- Policy Issue SECY-11-0152 contains a discussion on an emergency preparedness framework for SMRs that includes an example of a scalable Emergency Planning Zone (EPZ), based on the dose a distances from the site and utilizing the EPA Protective Action Guides (PAGs). The NRC has licensed several small reactors with an EPZ of 5 miles for plume (and 30 miles for ingestion), including the Fort St. Vrain High Temperature Gas-cooled Reactor (HTGR) (842 MWt), the Big Rock Point Boiling Water Reactor (BWR) (240 MWt), and the La Crosse BWR (165 MWt). Given the SMR passive safety features and the potential for reduced accident source terms and fission product releases, it may be appropriate for SMRs to develop similarly reduced EPZ sizes using a dose/distance approach.

2.7. Integrating Safety, Security, Operations, and Safeguards

The traditional design process for nuclear facilities bears certain similarities with the traditional engineering design process. While both begin with the identification of the requirements for the design, and both entail systematic stages that increase in the levels of analysis and detail resulting in a final design, the nuclear design process brings special characteristics and differentiators to the process, including an early design stage that evaluates the status of the technologies.

Design processes begin with the **identification of requirements** that the proposed facility should meet. Traditionally, these requirements include operating capacity and goals, regulatory requirements, life-cycle parameters, and expected delivery schedule. The second stage in the design for nuclear facilities is **pre-conceptual design**, which focuses on the identification and analysis of the status of any new technologies needed and that may be utilized in the design. This pre-work is specific to the nuclear design process and not only determines the status of technologies, but also identifies the research and development needed to establish the technical and functional specifications for any subsequent design work.

Following the requirements determination and pre-conceptual design, the core of the facility design happens during **conceptual design**. Conceptual design is focused on the generation, evaluation, and presentation of ideas to meet the identified requirements. The key is to move from pre-conceptual design to conceptual design by focusing on the functionality and on the operations that need to be executed by the facility. Conceptual design includes the design of the nuclear process leading to process optimization. This stage determines the degree and opportunity for innovation in a design depending on the nature of facility, market requirements, and the state of development of the relevant technology. The last step of the traditional process transitions to **detailed design**, which is focused on delivering a set of manufacturing documentation that meets the facility operational specifications and the business needs defined in the first stage.

Figure 1 illustrates the design stages, and associated deliverables, that are typically expected as the result of each of these stages during the traditional engineering design process for facility, process, or product design (The Design Society, 2011). Pre-Conceptual design stage and licensing expectations have been added to comprehensively illustrate the nuclear design process.

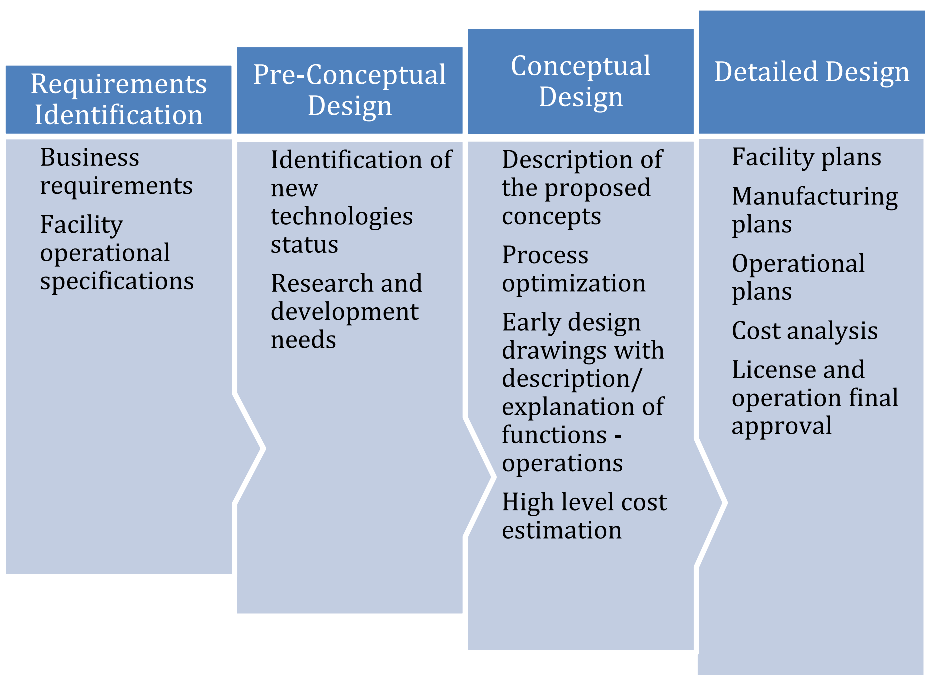

Figure 1: Traditional Design Process and Deliverables

3. Facility Licensing

The regulatory environment for licensing nuclear facilities calls for consideration of several factors in the design of a facility: safety, operations, security, and safeguards (SOSS). The compliance strategy associated with satisfying the licensing requirements that are related to these factors has a very significant impact on the final configuration and required staffing levels for the facility. Requirements that are only considered later in the design result in expensive retrofitting (Ingersoll, 2009), and can result in the final constructed facility incorporating some features that are expensive to safeguard and secure. Therefore, it's critical that the conceptual design of nuclear facilities focus not only on primarily operational requirements - much like traditional engineering processes - but also on incorporating safety considerations and licensing issue resolution before the conceptual design is well under way. It is also noted that conceptual facility designs are not perfect "on paper" and, typically, must evolve to some extent during siting, construction, facility startup, and operation.

The traditional lifecycle (from detailed design/licensing to include construction and operation/retrofitting/upgrades) illustrates the complexity and consequences that are introduced if the regulatory environment is not considered until late in the design process. Figure 2 shows the moment when safety, security, operations, and safeguards enter the process. Again, if the SOSS requirements are not considered early in the design phase, a larger effort is needed during the last stage, often requiring significant retrofitting to meet regulatory requirements. This effort could be prevented or minimized if SOSS were integrated into the early design of the facility, greatly reducing the need for retrofitting.

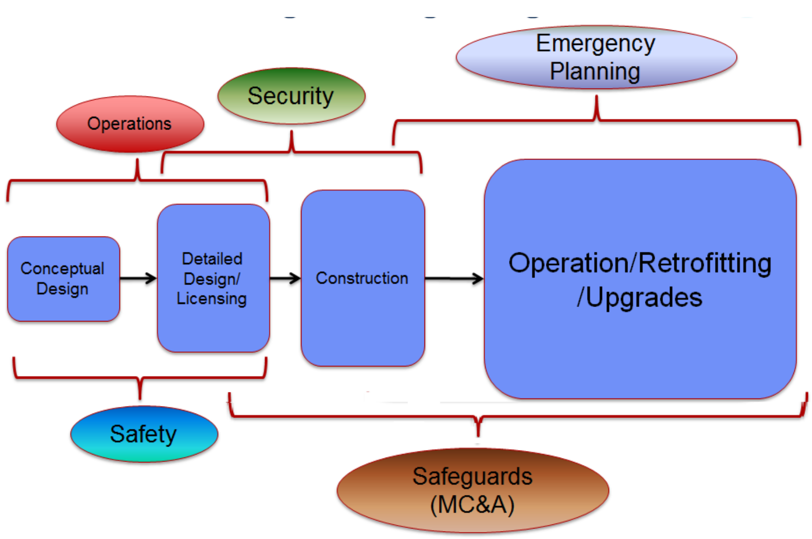

Figure 2: Traditional Lifecycle with Considerations for SOSS

Changes in design basis threats (DBTs), improved proliferation resistance, and safety requirements now require that SOSS be given consideration very early in the nuclear plant design process. The link between these factors is apparent. It is also apparent that an optimized balance between them will result in the efficient and effective accomplishment of the four goals.

3.1. The Proposed, Integrated Design Process for Nuclear Facilities

In 2002, Poong-Eil Juhn, Director of the IAEA Division of Nuclear Power, stated that SMRs' passive and inherent safety systems can be built-in, based on a multi-dimensional view that includes maintenance, operation, and management issues (Juhn, 2002). Darby, et al., (2007) documented that "the need for integrated safety, operations, security, and safeguards (ISOSS) is being stressed in new Department of Energy (DOE) orders and proposed in Nuclear Regulatory Commission licensing approaches."

ISOSS is a framework for integrating and harmonizing safety, operations, security, and safeguards into the design process (Darby, et al., 2007), and suggests that linking all four factors into the plant design enhances operation to provide a more efficient, cost-effective, and reliable plant (Rochau, et al., 2007). The integrated four factors of ISOSS, as used for nuclear facilities, are defined as follows:

- Safety – The activities and systems that protect people and equipment from harm or damage (e.g., fire protection, criticality safety, emergency cooling systems).
- Operations – The activities and systems at a facility that produce the facility's products (e.g., process, system components, and operators).
- Security – The activities and systems that protect assets from theft and sabotage (e.g., guards, access controls), also known as Physical Protection.
- Safeguards – The activities and systems that provide the material control and accounting systems, also known as Domestic Safeguards.

The ISOSS Framework (below) proposes a way to integrate and harmonize safety, operations, security, and safeguards during the design process. This framework can be used during the facility design process to incorporate the four SOSS factors, and to ensure that compliance with the regulatory environment is incorporated into the design and decision-making.

The steps of the SOSS framework are summarized below (Darby, et al., 2007):

1. Identify the regulatory requirements for safety, security, and safeguards. Requirements may contain a combination of prescriptive, risk-informed, and performance-based regulations.
2. Identify the SOSS expectations and performance measures. The regulations, particularly risk-informed and performance-based regulations, may likely utilize a set of performance measures and expectations in determining the adequacy of a design.
3. Facility Preliminary Design may likely be focused on meeting a set of functional requirements, while still incorporating accident prevention and mitigation.
4. The Design Analysis Process may be focused on ensuring that SSS are integrated into each step of the design. Integration would be an iterative process that would strive to

harmonize the design to meet all SOSS requirements, expectations, and performance measures in a cost-effective manner. This step would consider diverse scenarios, including “Identify Threats and Challenges to the Facility”, “Target/Hazard Identification”, “Response Analysis”, “Regulatory Guidelines and Licensing Technology Base”, and “Comparison of the Design to Performance Measures”, which would guarantee that, at every stage of the design, the SSS evaluations are compared against the established regulatory and performance criteria and the design is modified when needed. “SOSS Design Harmonization” would require that teams evaluating SSS maintain constant communication, allowing for the identification of potential conflicts in the design, as well as possible solutions.

Integrating SOSS into a nuclear facility requires two steps. First, the facility design must integrate the four factors; second, the operational facility must provide data to support the factors. To the extent that the data is generated intrinsically by the system, and that it is securely collected and processed, the reliability and trust in the facility will increase (Mendez, et al., 2007).

Each of the four functions responds to this framework in its own, specialized manner:

- Operations - striving to achieve product more efficiently;
- Safety - determining when to activate safety functions;
- Security - determining the security condition of the plant and preparing to respond; and
- Safeguards - determining the status of nuclear materials and preparing to report.

Each of these functions benefits from having information on the status of the other three. Therefore, integrating the information system has significant benefit. However, each of the four functions requires a level of integrity and assurance for this information. The result of the framework is real-time process monitoring with secure and verified information: totally transparent functionality.

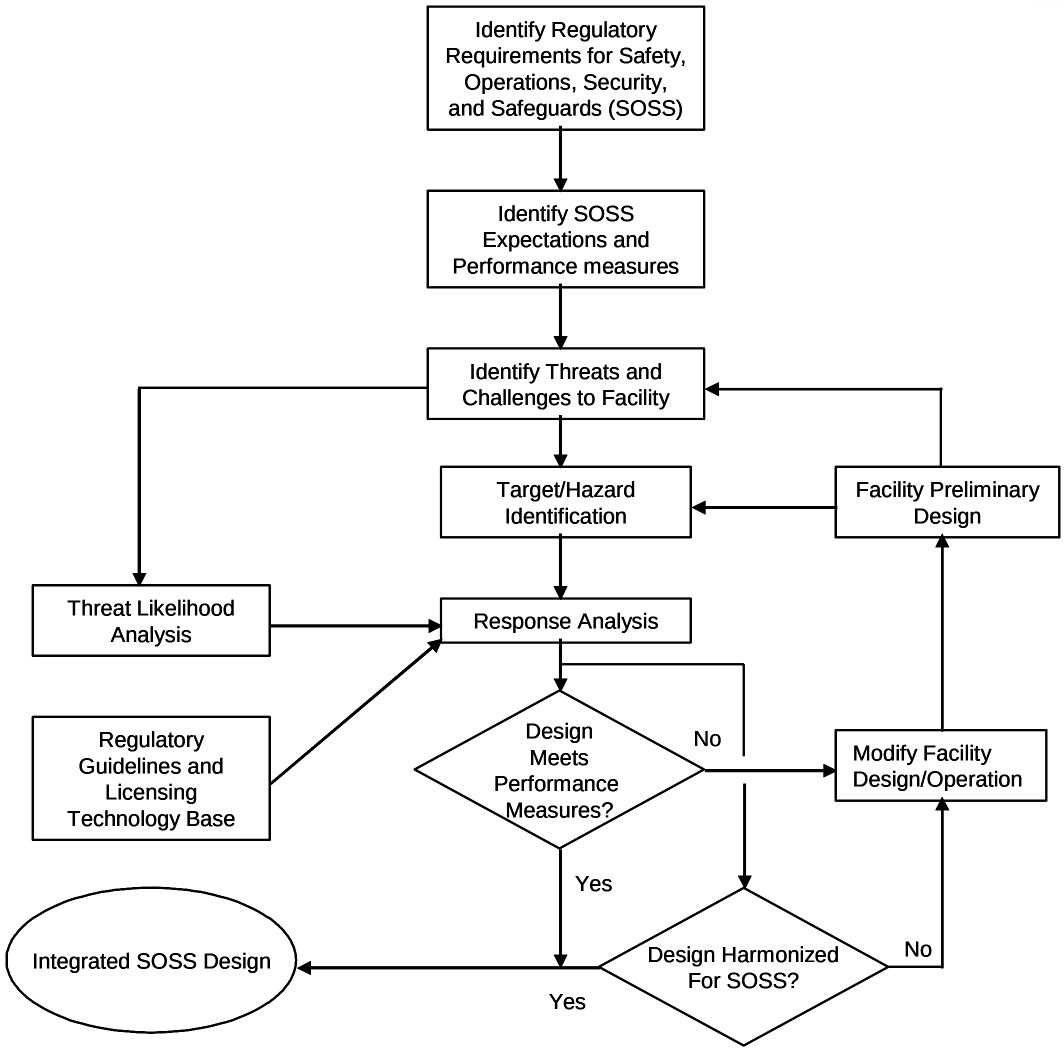

Figure 3: Framework for integrating SOSS during the design process

Much of the information necessary to support the four functions comes from a common source. Increasing the reliability of this information and securing it is of common interest. This is a basic tenet of a Transparency Framework (Love, et al., 2006). As applied to ISOSS, transparency is used to communicate not only with observers outside of the nuclear facility, but also with observers within the facility. This framework requires securing data at the lowest level of detail, demanding a certain level of technology readiness and design principles for application (Mendez, et al., 2007). The sharing of information among the different functional databases in real-time ensures that the most current information that is possibly available can be used by whichever functional unit needs it. For example, if the reactor is in a state requiring a maintenance procedure that causes a door which is normally closed to be opened, the maintenance procedure itself may be considered an operational or safety procedure. However, the door is now in an off-normal condition that could potentially allow easier access to critical equipment, thereby increasing the security risk. Information related to this procedure can be transmitted in real-time *without need for human transfer of the information*, if the appropriate sensors are installed and the information is shared among the operational, safety, and security functional units. This type of information transparency can increase the overall safety and security of the plant, since the human-based relay of information has a notoriously high unreliability (Kajtazi, et al., 2010).

4. Concurrent Engineering Design Framework for SMR Facilities

4.1. Basic Principles for Concurrent Engineering

The term "concurrent engineering"(CE) was first coined within the manufacturing industry as a business strategy to replace the traditional product development process with one in which tasks are done in parallel, and there is an early consideration for every aspect of a product's development process.

Traditional Engineering is a linear or sequential process that is performed for manufacturing, test, quality, and service departments; they interact in this sequential process in the **Review** and **Redesign** steps. Steps are performed one-by-one. In comparison, *Concurrent Engineering* is a non-linear process that constantly requires the contribution of manufacturing, test, quality and service departments. The process logistic allows each step to be executed almost simultaneously.

The CE strategy focuses on the optimization and distribution of resources in the design and development phases to ensure effective and efficient product development process (Berkeley Expert Systems Technology). CE can be defined as "the integration of interrelated functions at the outset of the development process in order to minimize risk and reduce effort downstream in the process, and to better meet customer needs" (Winner, et al., 1998). Multifunctional teams, concurrency of product/process development, integration tools, information technologies, and process coordination are among the elements that enable CE to improve performance (Blackburn, 1991)**.**

> ***Concurrent Engineering*** is a systematic approach to the **integrated**, **concurrent** design of **products** and their related **processes**, including **manufacture** and **support**.
>
> It is intended to cause the developers from the outset to **consider all elements of the product life cycle** from **conception** to **disposal**, including **quality, cost, schedule, and user requirements**. (Winner, Pennel, Bertrand, & Slusarczuk,1988)

4.1.1. Basic Principles in Concurrent Engineering

While several concurrent engineering models have been proposed since the early days of concurrent engineering (dating back to the 1980s), three concepts remain consistent as the primary factors for success:

1) setting and analyzing goals,
2) directing and controlling integration, and
3) fostering communication (Swink, Sandvig, & Mabert, 1996).

Most CE models were developed to address the early stages of product or process development, but others have expanded into the maintenance/monitoring/control stage of a process. A systems approach to service development in a concurrent engineering environment suggests breaking complex systems, especially those for facility management, into several key design stages: (i) process design; (ii) quality design; (iii) production-management design; (iv) capacity design; (v) management design; and (vi) physical and technical design. These designs are integrated and conducted systematically in the implementation of the project to raise the overall performance (Ching-Chow, 2007). Another framework advocates for the systematic implementation of CE, involving process, people, tools and technology, organizational support, metrics, buy-in, and benefits and barriers to success (Bhuiyan, Thomson, & Gerwin, 2006).

The centralization of the information and the use of information technology facilitate the CE implementation. Fecondo, et al. (2006), argues that companies implementing CE must redefine their requirements for collaboration and look for techniques and tools that help them to construct virtual organizations for electronic collaboration. Lee, Kim, & Bae (2001) suggest that, with the use of web-based systems, the companies can take advantage of concurrent engineering. In particular, Waurzyniak (2008) documented the demand of Product Lifecycle Management (PLM) solutions, software, and services, as well as how they can support a manufacturing environment from early-stage product strategy development and planning, to product engineering and manufacturing engineering, and onward, through product maintenance and support.

Several CE models were reviewed to identify the most relevant parallel that could be applied to the design, manufacture, and operation of nuclear facilities. Table 1 summarizes five basic principles identified through every model. In turn, each principle has been mapped to specification requirements in the SMR life-cycle.

Table 1: Basic Principles of CE applied to SMR Design

CE Basic Principles		CE Principles applied to SMR Design
1. Build multidisciplinary task-forces	→	Build the CE Team
2. Define product in customer terms, then translate into engineering requirements	→	Define performance and life-cycle specifications
3. Define process parameters	→	Define performance, licensing, and life-cycle specifications
4. Design for manufacture and assembly	→	Design for manufacture, transport, and assembly
5. Concurrently develop product, manufacturing process, quality control, and marketing	→	Concurrently develop of designs to meet all specifications, including operations and maintenance of facility

5. Requirements in a CE Design Process for Nuclear Facilities

A Concurrent Engineering framework for nuclear facilities must be able to support the design of SMRs, taking the facility through design, licensing, manufacturing, and continued operations – for however long the operation and ongoing maintenance would be performed according to pre-determined setpoints. However, CE was originally envisioned for short life-cycle products, taking the product from design to marketing and sales. It has not traditionally been used as a tool for the design of large facilities – and certainly has not been used for the design of a utility facility that has a long operational lifetime in a highly regulated environment. Furthermore, the traditional product development cycle for which concurrent engineering was first envisioned follows the product from design to sales and distribution, but there has been limited consideration for the operation and continued maintenance of the “outcome” of the design. These factors need to be considered when applying concurrent engineering to SMR facilities, thus engaging additional expertise in the early stages of the concurrent engineering team.

CE takes into consideration the input of experts across every stage of the design, manufacturing, marketing, distribution, and sales of a product. The insights, collaboration, and feedback provided by team-members during the design process allow for a cohesive product that is optimized to manufacture and sell. In the nuclear arena, the CE framework used for SMR design must also meet specific requirements for the end-product, leading to a nuclear facility that:

- Can **fulfill the energy demands** for which it is built,
- Is an **economical and functional alternative** when compared to the best existing alternative means for generating energy to meet the specified demand,
- **Meets regulatory requirements** to support the licensing and operation of the facility,
- **Supports cost efficiency** through continued operations and maintenance during the life of the facility,
- Considers **Safety, Security, Operations, and Safeguards** an intrinsic and integrated process through the design.
- **Shows flexibility in design, to allow for expansion and changes** throughout the operational lifecycle of the facility
- **Is designed to support long life-cycle terms and needs** since the planned facility life term is part of the initial design parameters.

Taking these requirements into account, this report introduces a CE approach that is engineered to optimize the design of a highly-regulated, energy-generating facility that will be operational for multiple decades. It is important that the CE framework be able to adjust and accommodate changing technologies and design needs. For example, while current LWR facilities are planned for life-cycles of 40 years initially, SMR design proposals have seen life-cycles of between 8 to 30 years without refueling (Juhn 2002), and even life-cycles of up to 100 years (Atkinson 2010). Considering the life cycle early on within the proposed CE framework ensures that the framework itself can be used to account for wide variability in the design parameters.

6. The Proposed CE Design Process for Nuclear Facilities

In general, the design and construction of new facilities requires a core team enabled with fully integrated communications and support services, using a Master Plan that addresses design, construction, demolition, supporting infrastructure, modernization, and maintenance of the facility (Thomas-Mobley, et al., 2005). This Master Plan can be executed using Concurrent Engineering techniques, with the support of Project Management.

The US General Services Administration (GSA) is supporting the use of building information modeling (BIM) for the management of facilities (GSA, 2011). The proposed CE design model will guide the design to support the execution of the manufacture, operation, and maintenance stages. Planning for facility lifecycle management during the design stages by incorporating BIM to leverage facility data will ensure that the facility is designed to meet the expectations of performance through its lifecycle.

The framework proposed (Figure 4) collocates Concurrent Engineering principles and business best practices within the traditional nuclear design process to facilitate differentiation between the two design frameworks (i.e., traditional and CE), while enabling familiarity within the two models. Therefore, the design of the new facility can be seen as a project with multiple stages: (1) Requirements Determination, (2) Pre-Conceptual Design, (3) Conceptual Design, (4) Detailed Design, (5) Manufacture and (6) Operations and Facility Maintenance.

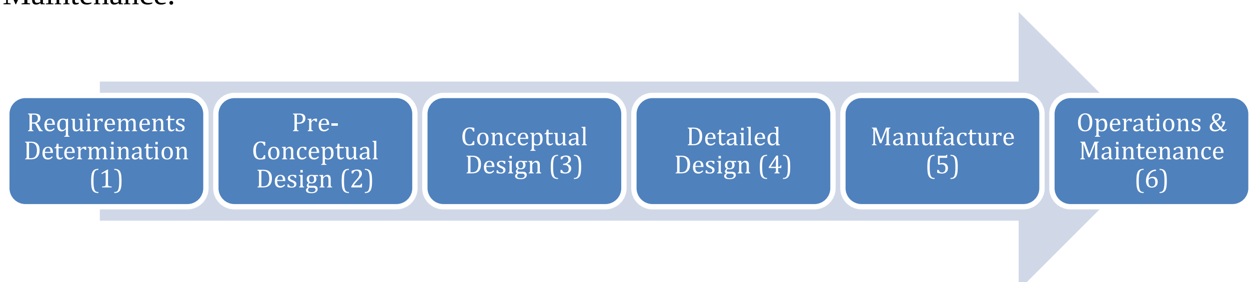

Figure 4: Design and Operation Project Stages

While these stages of the design and operations process are conceptually similar to the traditional nuclear facilities design model, the implementation of each stage is distinctively different in key ways.

Traditional design is a linear process that often requires the full completion of a previous stage before moving on to the next. The concurrent engineering model is iterative in nature, especially during the conceptual and detailed design process, enabling communication and establishing review procedures during the design to ensure that the end result is reached by taking into account concurrent input from all operational areas.

The **CE model** dedicates extensive time during the requirements determination stage to ensure that all facility requirements (operational and regulatory) are identified early in the process, and that all functional areas are represented during the design stages.
The CE model also dedicates extensive time during the pre-conceptual design stage to not only identify the status of the technologies and needs for R&D to be integrated, but also to define the rules for collaboration between the design team, setting the foundation for the design within a range of parameters for design. It also requires that all team members share the information that leads to the definition of their respective functional requirements to ensure that 1) all areas design with the same understanding, and 2) all areas are able to identify when design parameters may negatively impact other aspects of the design.

The CE model identifies the tools for collaboration, and builds on best practices from other industries to incorporate project management, effective teamwork tools and information sharing, systems balancing, facility lifecycle management, lifecycle cost analysis, and building information management to facilitate decision making and conflict resolution.

The CE model requires that manufacturing of the facility not be started until after the Detailed Design is completed and all team members, including operations and construction advisors, are in agreement that the requirements have been met.

The project, which takes the facility from requirements to operations and maintenance, should be managed through a Project Management Organization (PMO). The timeline and expected delivery schedule should be managed using project management techniques, while the contribution of a Project Manager should be included from the requirements determination stage through the lifespan of the facility.

Table 2, below, summarizes the key aspects that differentiate the two models.

Table 2: Traditional and Concurrent Engineering Design differences

Traditional Nuclear Facility Design	Concurrent Engineering Nuclear Facility Design	Highlights
Requirements Identification	Requirements Identification	CE is iterative, and includes Team identification, as well as Requirements identification. CE incorporates licensing requirements as core needs to ensure they are incorporated and to eliminate retrofitting.
Pre-Conceptual Design	Pre-Conceptual Design	CE enables consideration for R&D needs, while defining the parameter ranges of design for each design area.
Conceptual Design	Conceptual / Detailed Design	CE is highly iterative and identifies checkpoints for team design, procedures for individual design with active communication with other teams, and tools and best practices from industry to facilitate decision-making between design alternatives.
Detailed Design / Licensing	Detailed Design	CE considers licensing throughout the design, so detailed design focuses on identifying the final solution that meets all requirements, and on completing the detailed plans for manufacturing the facility.
Manufacture	Manufacture	Manufacture does not begin until facility plans are approved. The inclusion of construction representatives as advisors on the CE team facilitates moving from the design phase to manufacturing.
Operation / Retrofitting / Upgrades	Operations and Facilities Maintenance	CE supports operations and maintenance in the early design, designing for ease, and, at this stage, continues to provide the PMO and Team support identified during the design stages.

6.1. Requirements Determination

In the initial *Requirements Determination* stage, all the requirements and expectations for the operation of the facility must be documented. Identifying a project manager early in the CE process – as part of the initial stage of requirements determination – will allow for consistent vision on the project's scope and performance goals through the different stages of the CE design model. Figure 5 outlines the expectations of this stage. Through the identification of specifications and requirements, the PMO helps facilitate a discussion between designers and customers that allows requirements and constraints in the design to be clearly stated. This stage allows the CE team to establish quality standards and maximum acceptable product deviations that will allow for remote manufacturing and on-site assembly. It also allows the team to verify Standards and Regulations and to establish the task according to the personnel required based on traditional facilities.

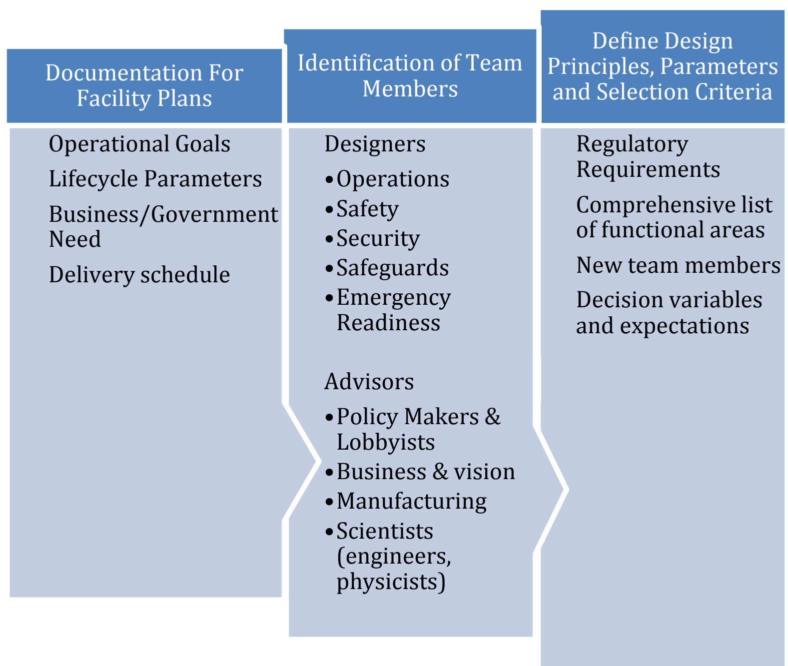

Figure 5: Requirements Documentation Stage

6.1.1. Documenting Facility Plans

Plans for a new facility, or even a new design, begin with basic expectations for operation and the delivery of goods. All requirements regarding operational goals, lifecycle parameters, delivery schedule, and business and government expectations should be identified. Relevant documentation must be completed with the following objectives:

(1) Setting the Project Scope,

(2) Project Time Management,

(3) Project Cost Management,

(4) Project Quality Management, and
(5) Project Procurement Management.

Operational goals need to be meaningful, realistic, and measurable, while priorities will be aligned according to seriousness, urgency, and the potential future impact of identified concerns on the operations (Zandin, 2001). When aligned, these requirements support the wise use of time, avoiding backtracking on the process and redoing tasks. Hence, the schedule should be reasonable, and should be established with the advisory of the team members.

Due to the nature of the product (small nuclear reactor facility), lifecycle parameters must be established to ensure that the end product will fulfill customer needs in functional terms, and at a reasonable total cost over the life of the product. Lifecycle parameters are driven by the acquisition cost, or product price, and the life support cost, or the cost for using the product. The lifecycle parameters need to be discussed with team members and the potential contractors, need to address the following factors:
(1) Technical performance required,
(2) Availability performance required,
(3) Cost requirements,
(4) Acquisition and maintenance resources, and
(5) Estimated cost for the number of years expected for facility operation.

Additionally, the commitments made during the definition of lifecycle parameters need to be allocated and addressed during the pertinent phases of the acquisition and the preliminary description of the model (Zandin, 2001). Additional lifecycle parameters need to be discussed with the team members, such as the available options for designing, from the beginning, a facility feasible for optimization and/or upgrades to the capacity (e.g., adapting to new nuclear technologies, etc.).

6.1.2. Building the CE Team

Concurrent engineering is based on collaborative teams that work together toward a common goal. CE teams are composed of experts representing every functional area of the product lifecycle. In the case of SMR facilities, experts in all things nuclear must be included early in the process. The team selected must have three key attributes:

- The ability to successfully address the inherent uncertainties of innovation;
- The ability to represent a broad range of professional skills, including engineering, science, marketing, manufacturing, operations, emergency preparedness, SOSS, and nuclear regulations;
- The involvement of primarily professional knowledge workers (i.e., individuals whose main responsibility and asset is knowledge, such as engineers, scientists, attorneys, etc.).

To accomplish a successful design that accounts for safety, security, and safeguards, while simultaneously supporting the continued operations and maintenance of the facility, it is necessary to bring together experts from all areas of the facility life-cycle, including the regulatory environment. This collaboration is difficult to accomplish in the late stages of facility design, because too much detailed engineering would need to be redone. The best opportunity is to form this team at the pre-conceptual design stage. A PMO should be identified to support the development of the project from inception.

Team members may be identified as:

- *designers* - those addressing technical and regulatory requirements pertaining to licensing. Designers include disciplines such as human factors, training, maintenance, operations, safety, security, safeguards, and emergency readiness; or
- *advisors* - those providing feedback on the validity of assumptions and representing the interests of the business. Advisors are policy makers and lobbyists, business & strategy representatives, manufacturing specialists, and scientists.

This selection of experts, under a documented and supported collaborative design process, composes an effective concurrent engineering team. In this environment, each expert representative holds equal rank and works to achieve a common goal. As the design evolves, each of the representatives has an in-depth knowledge and appreciation of the project requirements and the effect of the others on the process and the end result. This allows for productive discussion, informed decisions, and effective compromise.

The project manager, working as a Subject Matter Expert (SME) with the concurrent engineering team (formed by designers and advisors) will work together to complete the requirements-gathering and documentation. This stage will allow the CE team to identify whether additional team members need to be incorporated into the project, and to identify any constraints on the process.

6.1.3. Performance and Life-Cycle Specifications

The reactor requirements must be clearly stated prior to the early design. Performance and life-cycle specifications must be identified and openly discussed by the team. The lists shown in

Table 3: Performance and Life-Cycle Specifications may serve as a guide for the CE team during this process, but it in no way should they be considered comprehensive. The team must work together to clearly define the specifications for the facility across all factors.

Table 3: Performance and Life-Cycle Specifications

Performance Specifications	Life-Cycle Specifications
Energy generation	Maintenance
Output	Expected life
Refueling	Regulations
Technology	Personnel
Safety	Output-Throughput Demand
Security	Decommissioning
Operations	

6.2. Pre-Conceptual Design

Figure 6 shows that, once the project scope is set, the team will start the *Pre-Conceptual Design*, or Second Stage. This stage will develop the required pre-work according to the *project scope* and will function as the start point for the Conceptual Design. The CE team will hold a meeting to define the requirements and deliverables for the design of the new facility, according to their area of expertise/work: (a) critical parameters, (b) relations between parameters and functional areas, and (c) constraints.

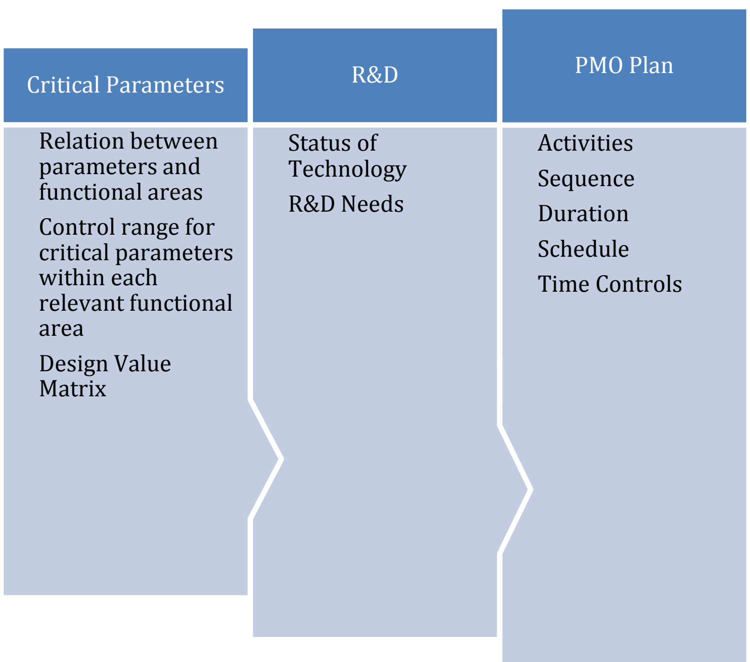

Figure 6: Pre-Conceptual Design Stage

Through iterative team meetings, after all of the facility specifications are identified, teams must enter into dialogue to understand the validity of the parameters identified for each area and to define the control range within which a design can be negotiated. A document should be developed that contains the requirements matrix and design range for each parameter. This document would provide each team member with an easy reference to allow for immediate communication whenever a design idea appears either to be in direct conflict with another design range or feature or to be outside the defined range. Simultaneously, each functional area will identify the status of relevant technologies, as well as research and development needs that may impact the design and implementation.

The Pre-Conceptual Design will provide the project manager with the necessary information to create the preliminary schedule for the project, which includes five steps:

(a) Define Activities,
(b) Sequence Activities,
(c) Estimate Durations,
(d) Develop Schedule, and
(e) Control Time.

6.3. Conceptual Design/Detailed Design

The Conceptual Design, or third stage, has two parallel processes: (1) Individual Design (individual contribution), and (2) Design Review Team Meetings (Iterative Meetings, Follow-up, and Final Pre-work Meeting). The team will now begin the design stage, ensuring that all performance and life-cycle specifications are met and are sustainable through the lifecycle. Performance specifications are addressed first, because they guide the minimum requirements needed for the facility to meet its stated purpose. The CE process ensures that any incongruences or conflicts arising from divergent specifications are identified, and the CE team works collaboratively to ensure that solutions are identified that do not compromise the end performance goals for the facility. Lifecycle specifications are also addressed in the same format.

This stage requires each team member to 1) develop an individual conceptual design (from their area of expertise) using the results from the pre-conceptual design stage, 2) address conflicting requirements and design parameters with affected team counterparts (during the individual and iterative design process), and 3) sustain team meetings to evaluate all aspects of the design.

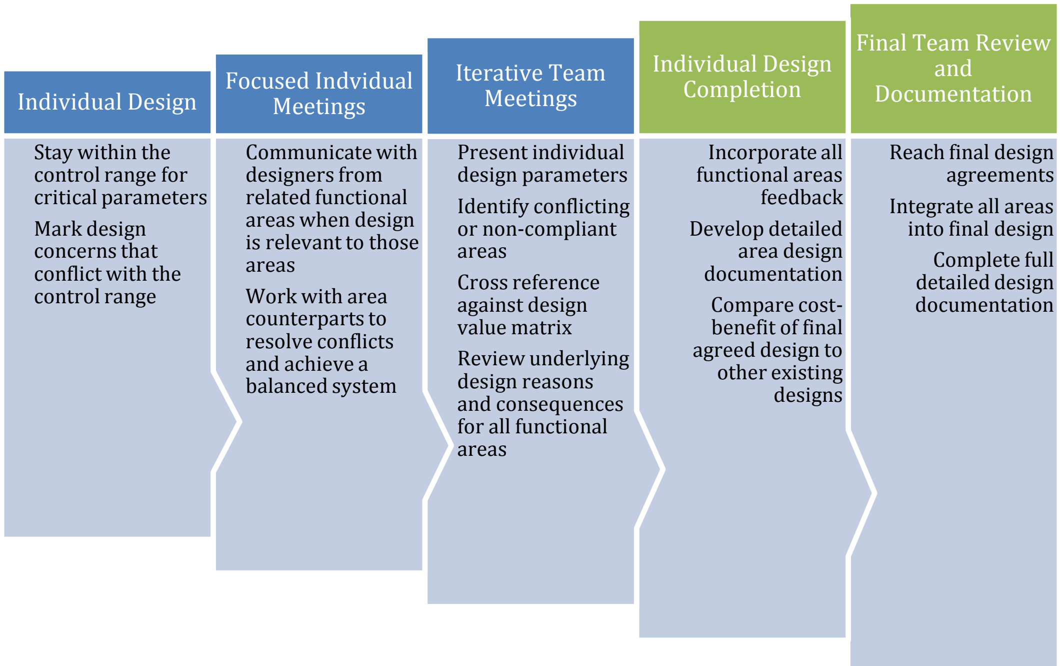

Figure 7: Conceptual and Detail Design Stages

Team members will work within the parameter ranges agreed upon during the pre-conceptual design stage. In addition, they will:

(a) remain within the control range for critical parameters and immediately communicate conflict and issues when those parameters cannot be met,

(b) communicate with designers from related functional areas when the design is relevant to those areas, and

(c) mark design concerns that conflict with the initial control range.

The team will be focused on the generation, evaluation and presentation of ideas to meet the requirements identified and to achieve 1) the scope and degree of innovation in the design of a small nuclear reactor facility, 2) the market/business/government requirements, and 3) the state of development of the technology to be implemented. The conceptual design will describe the proposed concepts, deliver the early design drawings (with descriptions and/or explanations of the functional areas), and estimate the high-level costs.

Between team meetings, team members will work individually, guided by the parameter controls, and will communicate with relevant counterparts to agree on design elements when any conflicts outside of the parameter controls are identified. They will iteratively bring in additional counterparts, as needed, when the design impacts other areas, or when coordination with other areas is necessary to reach a balance and compromise in the design.

Follow-up will also require that all team members participate in group meetings, during which they will present and discuss every individual's proposed designs. During these regularly scheduled review sessions, the team will:

(1) Present individual designs and a summary of the design parameters,

(2) Highlight conflicting or non-compliant areas by a cross-reference against the parameters matrix, presenting the final agreement reached with relevant counterparts,

(3) Review underlying design reasons and consequences for all functional areas, and

(4) Develop collective agreements.

Each individual design will be scrutinized and cross-referenced to discover constraints between the functional areas, find feasible solutions for constraints, ensure no additional areas would be affected by the design, establish whether additional research and development is needed, and create a solid Conceptual Design. Follow-up will be conducted, as required, and the project manager will be responsible for time management during meetings.

Processes and tools need to be available to allow for team collaboration, checkpoints, and decision-making to ensure a true CE approach is implemented. The Balance Model, along with the parameter metrics defined in the previous stage, may be used to facilitate discussion and provide alternative solutions to conflict. Over several iterations of design and discussion, facility lifecycle cost analysis may be used as a decision-maker between several design options. It is recommended that this stage also consider the creation and analysis of a list of contractors available to fulfill the demands of the design. Any special requirements that suppliers are expected to support during the manufacturing stage should also be identified, along with the name of at least one supplier that has the necessary capabilities.

Furthermore, in planning for continued operations and maintenance, the design conversations, from the conceptual through the detailed design, may benefit from several considerations that should support the expected lifespan of the facility. These considerations include:

1. Developing a written report that matches the operational requirements to the requirement owner. Owners need to be notified, in cases of conflict, to approve changes or resolve roadblocks.
2. Establishing communication protocols that govern all stages of the operation and maintenance to address issues, creating and defining the levels of notifications and escalation procedures. For Example: if SEVERE notify A, B, & C.
3. Planning for contingencies, if there is no flexibility in the regulations for SMR applications.

a. Identifying which tasks can be performed by multiple personnel and which ones are restricted to one, specially trained individual. This will help to create a cross-training schedule for readiness once the facility is completed.
b. Identifying the tasks and the personnel required to operate the facility based on job descriptions and background requirements. A thorough understanding of staffing needs will facilitate multitasking and cross-training. This will support the development of the smaller team that will run a small nuclear reactor that has the operational requirements of a big nuclear reactor
c. Establishing a list of possible customer and engineering requirements that may be modified for the short term (5 – 10 years), medium term (11 – 30 years), and long term (31 + years).

4. Creating a list of allowances required for possibly changed requirements
5. Developing a list of building requirements to fit possible changes (for example: bigger doors or roof areas that can be removed to allow entry of big equipment)

Finally, the *Detailed Design*, or fourth, stage has three processes. These processes are:

1. Individual Design Completion,
2. Final Team Meeting Review, and
3. Final Design Documentation.

The Individual Design Completion requires final team meetings to incorporate the design of all functional areas into one final and comprehensive design. The final design must be compared to other existing designs to analyze cost-benefits. The Final Team Meeting Review will allow the committee to reach a decision and to develop the final design agreements that will lead to the Final Design Documentation.

6.4. Manufacture

The early inclusion of construction and operations representatives into the CE team ensures a practical transition to manufacturing and operations, because the facility is already designed within accepted parameters to fulfill expected needs.

The manufacture stage of the process is divided into sequential stages, each of which must be completed before the next can begin. The stages are:
(1) In-factory manufacture of systems and system components,
(2) Transportation to the facility site,
(3) Site assembly and installation, including initial fueling, and
(4) Testing prior to “go-live” operations (see Figure 9).

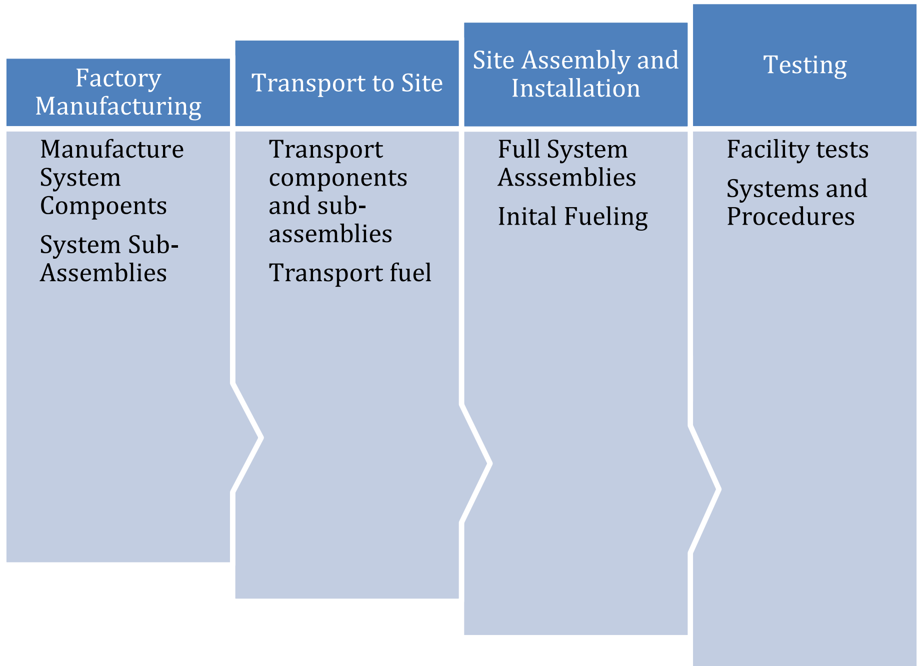

Figure 8: Manufacture Stage

The early inclusion of manufacturing representatives into the CE team ensures a practical transition from design to each of the manufacturing phases. Representatives of the manufacturing process serving on the CE team are responsible for ensuring the ease of construction, including an analysis of the vendors and suppliers available. This allows for a smooth execution of the build. Furthermore, procedures should also be put in place, *a priori*, to ensure the reliability of manufactured components, the ease and efficiency of transport and assembly, and adequate processes for testing.

6.5. Operations and Facilities Maintenance

The final stage of the process encompasses the operations and continued maintenance for the facility. If the CE design process is successful, and the design is implemented effectively during the manufacturing stage, this final stage is supported by a facility that:

- integrates licensing requirements early in the design, and
- takes into consideration performance, conflicting requirements, and potential changes throughout the lifecycle.

To support this stage, the CE team will facilitate the early inclusion of Building Information Modeling (BIM) as a facility lifecycle management strategy. BIM facilitates the ongoing flow of information through the manufacture, activation (installation and testing), operation, maintenance, and decommissioning stages. Ultimately, the early design and BIM will also support decommissioning of the facility at the end of its expected life. BIM procedures are detailed in the next section of this report.

7. Tools to Support the Proposed CE Design Process

The Balance Model, Lifecycle Cost Analysis, and Building Information Modeling are useful tools to fulfill the procedural and optimization stages of the CE Design Process.

7.1. A Balanced Work System

All variables, including performance and life-cycle specifications, as well as the requirements to execute those, can be allocated into five system elements. This concept, taken from the industrial engineering field, is known as the human factors "balance model" (Smith, et al., 1989). The balance model, later called "balance theory," was originally designed as a means of evaluating on-the-job stress and identifying strategies for stress reduction. It has since transitioned into a more generalized tool in the human factors field, providing a simple strategy to visualize the complexities of any work system and to provide opportunities to manage system changes.

The theory suggests that every work system is formed by five core elements, and that a change in any one of the elements will have consequences and will bring additional changes to each of the other elements. Early assessment of the consequent changes allows designers to identify required adjustments and propose solutions prior to implementation, to better support the stability of the system. The five elements of the work system include 1) the people that act and interact with the system, 2) the tasks performed, 3) the tools and technologies used, 4) the environment within which the system operates, and 5) the organization that defines and controls the system.
The "**people"** element considers all personnel and staffing needs, and their intrinsic characteristics. The analysis defines the roles and responsibilities of each job, what the staffing needs are for every task, and the profiles of people hired at all levels.

The "**task**" element defines all the activities that need to be completed, building up to the outcome of the system. One, or several, system outcomes must be identified, providing the scope of the analysis. For each outcome, a process and interim stages of the process are then considered. The analysis of each process provides the individual tasks that must be performed to reach the outcome of the system.

The "**tools and technologies**" element should consider all the tools needed to complete each of the tasks defined, including the degree of automation and reliability in the technology, the tools that an operator would need to perform the task, and the availability, complexity, and performance of the tools needed.

The "**environment**" describes the environmental variables within which the work system operates. These variables are normally defined for physical climatology and geographical environments, but can also relate to the social and political environments that may affect the system.

Finally, the "**organization**" details the policies and procedures put in place to regulate the work system. What does the organizational structure look like? What are the escalation procedures, maintenance procedures, and emergency response plans?

A nuclear facility system can become very complex when considering all the interacting variables. Once the elements of the work system are defined, analysts can visualize the different relationships that may be built to effect change. Within this framework, consider the following scenario: A LWR facility (Tools and Technologies) with has a defined set of parameters for each of the other elements of the work system. As a primary change, replace the LWR with an SMR facility. Assume that the system goal remains consistent: the generation of electric power through nuclear processing.

However, within this scenario, all the variables that affect the system will be affected by the change in the technology element. For the purpose of this report, the system is simplified to account for a few selected variables deemed relevant to support the successful continued operations of a nuclear facility in a strict regulatory environment.

Figure 8 presents a sample of the variables that play a role in analyzing the SMR work system, and how the system variables may be allocated to each of the five elements.

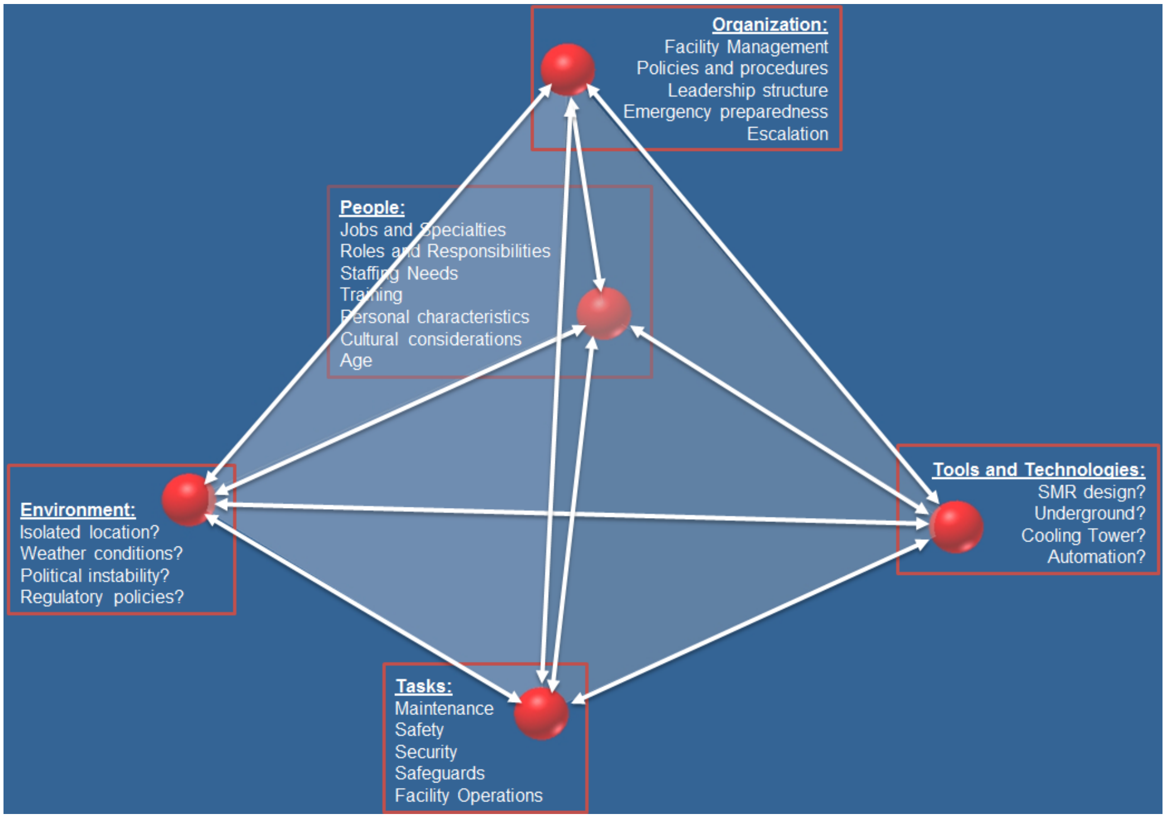

Figure 9: SMR Work System

(Each of the elements of the SMR Work System presented in Figure 8 is discussed, in detail, below.)

- **People** – For the SMR exercise, the roles and responsibilities of the jobs to be performed, the profiles of those hired to complete the jobs, along with their intrinsic characteristics and training, and the staffing needs to meet the demand must be identified.

- **Task** – For the SMR exercise, the primary task is the generation of electricity through nuclear processing using an SMR. This ultimate outcome, along with the processes and sub-processes that lead to it must be defined. The subtasks that lead to this outcome include the following: Operations, Maintenance, Safety, Security, and Safeguards.

- **Tools and technologies** – For the SMR exercise, the different SMR designs can be considered individual technologies. A selected group of variables that help characterize or distinguish between designs can be isolated as differing factors, including the cooling system, refueling needs, degree of automation, etc.

- **Environment** – For the SMR exercise, this analysis includes the location, and the characteristics of that location that define the need for an SMR facility. The analysis should consider whether the SMR will be located on an island, a zone prone to environmental disasters, or in a politically unstable country, and should identify the details that make one location different from another. Furthermore, for nuclear facilities, the environment should also consider the conditions that must be maintained to support external regulatory requirements.

- **Organization** – In the SMR exercise, the organization can be defined as 1) the structure identified to address the management of the facility, including organizational structure, policies, and procedures, and 2) the organization to respond to and/or address different regulatory requirements, such as emergency preparedness and escalation.

Due to the nature of SMRs, the core difference in the size of the facility, its capacity for power generation, its location, and its operation and maintenance characteristics, the entire work system should be scaled – up or down – to account for the new technology designs. What are the new roles and responsibilities of the jobs? Are there differences in the staffing needs? Do existing regulations still make sense for the capacity for power generation? What are the cost values across all the elements that will make a change in technology relevant and practical to government, business, and the community in general? The arrows indicate that a change in one variable may affect the other elements, and provide insights into what reactions could be recommended to support the change.

There is a significant level of iteration that can be accomplished through the application of the balance model to the SMR design process. Changes and reactions in each system element must be considered during the design stages of the new facility. Primarily, the design process should result in an already balanced work system, considering which variables in the new technology being designed can affect the change, the magnitude of the impact across the work system elements, and how the design can assist to mitigate, equalize, or optimize the reaction in other system elements. Facility designers must identify:

- The variables in the design that affect the change,
- The reaction to the change by the different system elements,
- Whether the reaction is an improvement or a detriment, as compared to the previous system,
    - If a detriment, which elements can be adjusted to control the change, including adjustments intrinsic to the new design, and
    - If an improvement, how the system can be optimized at the facility design to effect additional positive change.

Table 4 presents scenarios that describe the iterative nature between the elements in a nuclear system, as well as areas where balances and reactions can be relevant for the design process.

Table 4: Sample scenarios for System Balancing in SMR Applications

SMR Scenario/Requirement	System Reaction Alternatives	System Elements Involved
Staffing levels increase Lifecycle Costs to the point that SMRs are not economically viable.	Design features increase safety, safeguardability, and security, so that staffing level can be decreased. Personnel are cross-trained for operations AND Emergency Response to decrease staffing levels. Organizational policies allow for cross-training and job rotation. Remote monitoring is enabled.	Organization: People, Tasks, Environment, Organization, Tools/Technology
Facility energy output is greater than forecasted output.	Multi-modular approach allows adding modules for increased output.	Task: People, Technology, Organization
SMR located in isolated, Earthquake-prone area[1]	SMR technology makes SMRs much less prone to seismic risk.	Environment: Technology, Organization, People, Task,

7.2. Life-Cycle Cost Analysis

Life-cycle cost analysis (LCCA) is a method for evaluating all relevant costs over the performance life of a project, product, or facility (Gager, 2012). This method takes into account the first costs, including capital-investment, purchase, and installation costs; future costs, including energy, operation, maintenance, capital-replacement, and financing costs; and resale, salvage, or disposal costs over the life of the project, product, or facility.

The idea behind calculating LCCA is to maximize the costs by comparing them to alternative choices that are similar, yet different in cost structures. To calculate LCCA, the initial cost; the expected life (usually expressed in years); expected average yearly costs for maintenance, operation, and repair; maintenance and repair costs that occur only every few years, averaged over the time between occurrences; costs for operation

[1] While this scenario is an unlikely use of US technology, based on the NRC licensing process for reactors, it is presented as an example of the variable applications of systems balancing.

(including fuel, electricity, and water use); as well as any ongoing costs, salvage and other residual value, or the best estimate of each, must be available for comparison during the design.

Life Cycle cost is defined as "the customer total cost plus other expenses incurred during the lifetime of the product", and is expressed with the equation:

$$LCC = LCA + LSC$$

where $LCC = life\ cycle\ cost$

$LCA = acquisition\ cost\ (product\ price)$

$LSC = life\ support\ cost\ (user\ cost)$

LSC costs include corrective maintenance, workshop maintenance, preventive maintenance, spare parts, initial investment, and substitutes for future consumption, maintenance tools and equipment, documentation, training, operation, and lost production due to downtime, among others. The functional requirements related to the life cycle costs need to evaluate the availability of performance and include:

(1) Reliability or failure rate (MTTF = mean time to failures),

(2) Maintainability (MTTR = mean time to repair),

(3) Supportability (MTW = mean time waiting OR/AND, MLDT = mean logistics downtime, AND others).

To understand the theoretical combinations of requirements, the requirements can be organized and classified as shown in Table 5 (Zandin, 2001).

Table 5: Life Cycle Cost Matrix

	Availability	Maintenance Costs	Reliability	Maintainability	Lifetime
Downtime causes huge costs	⦿			⦿	
Operation is a must, e.g., a safety device			⦿		
Failures cause or may cause serious consequences			⦿		
Large purchase price and long technical lifetime	⦿				⦿
Maintenance costs is an essential part of life cycle costs		⦿			
Maintenance times cause an essential part of life cycle costs		⦿		⦿	

Both quantitative and qualitative techniques should be used to evaluate the Life Cycle Costs. The quantitative evaluation aims to address the availability of performance requirements to be fulfilled by contractors or service providers, which contractor/service provider offers the best functional availability to meet the specified operational conditions, and which contractor/service provider offers the lowest expected cost for acquisitions, operation, and support during the lifetime of the facility under the specified operational conditions. The qualitative evaluation requires assessing product characteristics that do not lend themselves to numerical representation.

The Life Support Cost (LSC) should consider the following:

(1) Calculation of failure rates, repair times, and costs of consumption of spare materials,
(2) Calculation of key figures expressing product availability performance characteristics,
(3) Calculation of the accumulated LSC according to the specific project model (equation)
(NOTE: this value is added to the acquisition cost to obtain the total LCC), and
(4) Revision of the calculated results through sensitivity analysis, and the presentation of the compiled results for each contractor/service provider/advisor.

7.3. Facility Lifecycle Management through Building Information Modeling

The Facility Management Journal (FMJ) provides a basic definition for Building Information Modeling (BIM) as a concept with two key elements: 1) object intelligence (the ability to associate material and assembly data with graphic elements), and 2) three dimensions (complete three-dimensional graphic representation of buildings) (Schley, M. (n.d.)). The FMJ provides a more comprehensive definition from the construction company, M.A. Morteson, in which they suggest that the BIM must have the following characteristics (Schley, M. (n.d.)). The BIM must be:

2. Digitally spatial (3D),
3. Measurable (quantifiable, dimensionable, and queryable),
4. Comprehensive (including design intent, building performance, manufacturability, and including sequential and financial aspects of means and methods),
5. Accessible (to the entire Architect-Engineer-Contractor/owner team through an interoperable and intuitive interface), and
6. Durable (usable through all phases of facility life).

The use of this model may be a step further into the use of advanced monitoring and transparency systems recommended by Rochau (2007).

The creation of a new facility for a small nuclear reactor will require a BIM for managing the following stages:

1. Manufacture

BIM software programs can benefit the building design and manufacturing through:

- the use of better management of information,
- three-dimensional views and walkthroughs for better visualization; and
- various types of building analyses in which other systems can be integrated (e.g., energy analysis programs).

Enabling this technology is a key component to the identification and management of SOSS system status. The construction stage can benefit with the tracking of construction phases, coordination of space, and schedules. In addition, software tools for clash detection can provide ways to reveal layout errors in advance.

2. Activation (Installation and Testing)

Planning for the activation of a new facility incorporates the processes of identifying, defining, organizing, and facilitating all of the tasks that are required for the occupation of the new facility in a logical, timely, safe, and cost-effective manner. Activation planning involves anticipation of and control over two types of issues. These issues can be classified as:

- **Logistics** - which include the planning and implementation of the facility-related aspects of the project, and
- **Operations** - which include planning for new processes and practices that define the way that the organization will conduct business. (Wilson, 2004) Wilson's seven guidelines for activation planning include:
  a) Use multidisciplinary teams to drive the planning stages and ensure that cross-functional processes, as well as enabling elements (e.g., information technology, human resources), are clearly integrated within process and activation plans.
  b) Equip planning teams with the necessary knowledge and tools to effectively complete their work. This may include training in meeting facilitation, as well as specific orientation to project objectives, macro-schedules, and guiding principles.
  c) Provide consistent, real-time communication of project schedules and plans to all relevant constituencies, including planning teams, medical staff, employees, and the community.
  d) Develop a database of activation issues, questions, and answers that is accessible to interested parties. Many organizations have adopted intranet capabilities to serve this need.

e) Assign a project champion to coordinate, facilitate, and drive all aspects of activation planning and implementation, and ensure that this individual has adequate time allocated to fulfill this role.
f) Make decisions in a timely manner, and communicate the decisions across the planning organization.
g) Do not underestimate the time and dollar investments that activation planning and implementation will require.

3. Continued Operations and Maintenance

Several benefits of maximizing BIM during the operation of the building can be applied in the areas of:

a) Preventive Maintenance - BIM software can provide tools for equipment that requires regular inspection and upkeep (e.g., heating, air conditioning, electrical distribution systems, etc.)
b) Space Management - This area requires the integration of building data with human resources data, providing a reduction in vacancy and real estate expenses.
c) Energy Efficiency Initiatives- BIM systems helps to identify energy performance by facilitating analysis and comparison of alternatives.
d) Base of ongoing changes - BIM provides an easier means of representing three-dimensional aspects of the building (especially in mechanical systems.) BIM models can carry extensive data about assemblies, finishes, and equipment items.
e) Life Cycle Management - BIM provides value in managing relevant data about current building conditions, and facilitates the analysis of alternatives. This can be created by embedding data on life expectancy and replacement costs in BIM models, which can help an owner understand the benefits of investing in materials and systems that may cost more initially, but that have a better payback over the life of the building.
f) Building automation systems - This can provide real-time monitoring and control of electrical and mechanical systems. FMJ mentions that effective building operation is critical to achieve potential energy savings. For nuclear systems, this functionality may provide a strong basis for transparency.
g) Keeping the BIM alive - FMJ suggest the use of technology that works bi-directionally between the BIM system and other building management systems, instead of one-way migration of data, to enable the BIM model to retain its usefulness throughout the life of the building.

4. Decommissioning

   A nuclear facility, and certainly small modular reactors, must consider decommissioning as a natural stage of the design process, foreseeing the need to shut down and discharge the facility when its designed life-cycle expectancy is fulfilled.

   L.E. Boing (2005) identified ten key actions that should be considered prior to starting a decommissioning strategy. These actions are:

   1) Information exchange,
   2) Communication,
   3) Site/facility history,
   4) Waste stream analysis,
   5) Hazards assessment,
   6) Estimating and understanding the cost to complete the work,
   7) Technologies needed to perform the project tasks,
   8) Conduct of final status surveys,
   9) Procuring specialist support, and
   10) Teamwork.

   From these ten key actions, the actions related to estimating and understanding the cost to complete the work and technologies needed to perform the project tasks can be performed using information systems. Information systems that analyze costs, such as accounting systems, can track depreciation on equipment, land, etc. From a technology point-of-view, there should be no obstacle in the technology area that impedes the decommissioning of a facility (L.E. Boing, 2005). In fact, many decommissioning technologies for decontamination, dismantlement, and all other related technical areas are available in an off-the-shelf configuration. The International Atomic Energy Agency (2008) has documented a series of innovative and adaptive technologies that can be used for the decommissioning of nuclear facilities.

8. Future Work

Although much has been achieved in researching the concepts that go into this framework, there is still work to be completed. The obvious next step is to apply these concepts to a real SMR system. The DOE is currently evaluating the status and technical maturity of three advanced SMR design types. Further future development of these design types could benefit significantly from the early application of the CE process. The designs are the Sodium Fast Reactor (SFR), the Molten Salt Reactor (MSR), and the High-Temperature Gas-Cooled Reactor (HTGR). There are multiple other SMR designs available, including the Lead-Bismuth-cooled reactor and SNL's Supercritical CO_2 Direct Cycle Gas Fast Reactor (SC-GFR).

The success of this concept depends heavily upon implementation in the early stages of design – preferably beginning in the pre-conceptual design phase – and continuing throughout the development of the SMR. As such, it is paramount that an SMR design be identified and that work is begun on the implementation of this CE concept to the design. Continued use of this concept is expected if it can be applied successfully in its initial application. Thus, it is advisable that this handbook be used in the near future to guide the development of an SMR design that is still in the pre-conceptual design phase.

9. Conclusions

A critical consideration in the deployment of new nuclear facilities is the cost of manufacturing and long-term operation and maintenance. Because nuclear facilities are highly regulated, these costs can rapidly escalate to maintain compliance with regulatory requirements, especially if the requirements are not considered part of the facility design. Facility retrofitting and increased operational costs to fulfill safety, security, safeguards, and emergency readiness requirements may be a major consideration in the success of nuclear technology as an alternative source of energy.

This report introduced an innovative approach that supports the design of nuclear facilities, in particular small modular reactors, to ensure that the facility is designed to comply with regulatory requirements. The framework incorporates the regulatory environment and the continued operation of the facility into the early design stages, eliminating the need for costly retrofitting and additional operating personnel to fulfill regulatory needs. **The goal is to decrease the integrated lifetime cost of building and operating advanced SMR facilities.** Advanced SMRs present a lot of potential, but the upfront build and lifetime costs of operation may not be economically feasible, unless changes are made to the status quo of nuclear facility deployments.

In a previous report, a project team evaluated the existing regulatory requirements that address safety, security, operations, safeguards, and the emergency readiness of nuclear facilities, and how these may be applicable to the design of small reactors. In this report, the focus is to put forth a design process that will facilitate the integration of regulatory requirements early in the design. The process supports the manufacturing and operational stages by allowing designers to identify and integrate requirements into the design, building for contingencies, and balancing conflicting needs.

The work pulls together best practices that have been applied successfully in other industries:

- **Concurrent Engineering** frames the procedural stages, from defining the expectations of the facility deployment, through the identification of regulatory requirements, to the preconceptual, conceptual, and detailed design stages. CE calls for a team of subject matter experts to be formed early in the process. This team is in charge of open and continued discussion on the design, working together to ensure that all requirements are incorporated in a manner that does not conflict with or hinder operations in other areas of the facility.

  The CE framework supports a continuous and iterative design process that ensures that all requirements are addressed and that any conflicts are identified and resolved as part of the process. This results in a final comprehensive design that is completed before the manufacturing stage begins, eliminating the need for costly retrofitting.

The addition of a Project Manager to execute the structure of a **Project Management Organization** is critical to the time management and success of implementing CE. The early inclusion of a **PMO** to the CE framework will allow for the facility design and operations to be treated as a project: with monitored activities, in a required sequence, with a defined duration for each task, and scheduled in a controlled timeframe.

Throughout the proposed CE framework, all project contributors have the required tools for effective communication, and are supported by a Project Manager who encompasses the long-term vision of stakeholders. The combination results in the timely execution of the project design, manufacture, and operation.

The use of **ISOSS** will lead to achieving a more efficient, cost-effective, and reliable plant (Rochau, et al., 2007). ISOSS ensures that safety, security, operations, and safeguards are considered thoroughly and are integrated into the design. Emergency readiness requirements are also considered as part of the facility design process.

The **Balance Model** is introduced as a tool to document conflicts between functional areas and to identify balancing strategies for resolving conflicts between the requirements. A balanced work system approach allows designers to consider the entire spectrum of the system (people, task, tools, environment, and technology) to find alternatives for conflict resolution, including defining the operations, procedures, and training needs for facility personnel.

Life-Cycle Cost Analysis (LCCA) is proposed as a variable for decision making. It allows the CE team to evaluate different design components and to understand the long-term cost and benefit of each option. The use of LCCA will provide a clear view of the relevant costs from the initial design stage through the decommission stage of the facility (Gager, 2012).

Facility Lifecycle Management with Building Information Modeling (BIM) is encouraged to support the Build, Activation, Continued Operations, and Decommissioning of the facility. This technology, if considered early, can be incorporated into the design to allow for controlled monitoring of operations, and may even support efforts for nuclear transparency.

The methodology proposed should be incorporated into the pre-conceptual through the early design stages of facilities, seeking a cost-effective design that meets both operational efficiencies and the regulatory environment. If executed properly, the proposed framework will allow for the building and continued operation of a facility that is designed to be cost-efficient, and that assures compliance with the full spectrum of the regulatory environment.

Given the state of the art, the current and future needs, and the recent interest in Small Modular Reactor technologies, the implementation of the framework described could not be timelier. To ensure that the deployment of SMR is effective and cost-efficient, the CE framework proposed needs to be incorporated now, while SMRs are still in the pre-conceptual to conceptual stages of design.

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