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Design Basis Model for Hosting Small Modular Reactors

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Changing the World's Energy Future

Ronald David Claghorn

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Abstract. To provide energy security and head off further increases in global temperatures, an aggressive transition from fossil fuels to other types of energy implies the need to possibly construct hundreds of nuclear power plants in the near future. However, the real and perceived risks of nuclear energy remain a significant impediment to that transition.

This paper describes a comprehensive work process that combines the rigor of model-based systems engineering (MBSE) with 1) the Idaho National Laboratory's (INL) decades of experience with small reactors and with 2) modern project delivery processes. The objective is to reduce the risks of building new facilities or converting existing facilities to nuclear power generation.

Keywords. Nuclear Energy**,** Design Basis, Model-Based Systems Engineering, Nuclear Reactor Infrastructure.

Introduction

Amid the world's growing energy needs, reducing reliance on imported fossil fuels has become the top energy security priority. The International Energy Agency (IEA) defines energy security as the "uninterrupted availability of energy sources at an affordable price" (IEA 2023). Similarly, the United Nations Sustainable Development Goal 7 (SDG 7) aims to ensure access to affordable, reliable, sustainable, and modern energy for all (UNEP 2021).

No less important is the climate crisis. Reaching net zero emissions (NZE) of greenhouse gases by 2050 requires a rapid and complete decarbonization of electricity generation and heat production. (IEA 2022)

Nuclear power plants (NPPs) with their 413 gigawatts (GW) of capacity operating in 32 countries, contribute to both energy security and emissions goals by avoiding 1.5 gigatons (Gt) of global emissions and 180 billion cubic meters (bcm) of global gas demand a year. (IEA 2022)

Wind and solar power are expected to lead the push to replace fossil fuels (IPCC 2022). However, their output is determined by weather and daylight. There are also aesthetic and environmental objections to the use of large amounts of land to produce significant amounts of power (Stevens, 2017).

Batteries assist wind and solar power generation by providing short-term flexibility and absorbing fluctuations on a per-minute or hourly basis. However, they are not suitable even for medium-energy storage (Srikanth 2023).

Batteries also present specific challenges related to critical minerals required for the manufacturing of batteries IEA (2023). While fuel material sourcing is also a problem for NPPs, a key, nearly unique, characteristic of nuclear energy is that used fuel may be reprocessed to recover fissile and fertile materials to provide fresh fuel for existing and future nuclear power plants (WNA 2020).

In contrast to wind and solar, NPPs use land very efficiently (Stevens, 2017). Their grid integration costs are also much less than those associated with wind and solar since they generate power in all kinds of weather and throughout the night (Srikanth 2023).

So, wind and solar power need to be complemented by dispatchable (on demand) resources. As today's second largest source of low emissions power after hydropower, and with its dispatchability and growth potential, nuclear – in countries where it is accepted – can help ensure secure, diverse low emissions electricity systems. In IEA's Net Zero by 2050 scenario, nuclear power must be doubled from 413 GW in 2021 to 812 GW in 2050, with annual capacity additions reaching a record high of 27 GW per year in the 2030s (IEA 2022).

The nuclear industry, however, has a long history of failing to deliver projects on time and on budget (Eash-Gates 2020). Further, restrictions on nuclear power remain in certain countries, driven by concerns about safety and waste. To fulfill its role in NZE objectives, nuclear power must overcome these obstacles.

Modularity

To avoid some of these disadvantages of NPPs, various entities worldwide intend to construct Small Modular Reactors (SMRs) at places such as retired coal-fired power plant sites (TerraPower 2021). This also enables the entities to reap the benefits of reusing existing infrastructure like grid and water facilities without acquiring land beyond the existing site boundary.

SMRs, by design, have a small core and small source term compared to conventional NPPs. Small structures are less vulnerable to seismic events. SMR designs are also simpler than those of conventional NPPs and include several passive safety features, resulting in lower potential for unsafe radioactive releases into the environment (Liou 2021). The amount of spent nuclear fuel stored in an SMR site will also be lesser than that in a conventional NPP using larger amounts of uranium fuel. Therefore, several studies have concluded that SMRs can be safely installed and operated in several thermal power sites which may not meet the stringent emergency planning zone requirements for conventional NPPs (Hansen. 2022).

The modular approach is a well-used strategy for simplifying the design and construction of complex systems and is certainly consistent with the systems approach to engineering. With the modular design approach, a complex system such as a an NPP can be broken down or divided into smaller and simpler components that are independently designed and manufactured. Each of these components is then integrated (or assembled) to form the final NPP.

The distinct advantage of a modular design is the use of proven, or at least well-worked, concepts, subsystems and components that can be reused multiple times to create a robust, scalable system. In this method, a significant portion of the construction is performed off-site in factories where modular components are built in different workstations, assembled on the production line, and shipped to the site for installation. Recent advances in monitoring and control of factory processes are making modular construction methods even more common due to the advantages offered in terms of safety, quality, and productivity for projects (Panahi, 2023).

And so it is with nuclear energy. A small modular system, as in small modular reactors (SMRs) up to 300 megawatts electric (MWe) and the even smaller microreactors up to 10 MW(e), present an attractive option compared to large, NPPs of 700+ MW(e). The smaller size of SMRs, and the even smaller microreactors, are a good fit for applications that need a local source of heat or remote / austere microgrids. This would include dedicated industrial applications such as hydrogen production and district heating where wind, solar, and the electrical grid are not dependable enough during deep winter months in remote locations.

Further, microreactors can be factory-fabricated and more readily deployable. While diseconomies of scale for microreactors may tend to raise their costs per energy output (MWh) relative to large NPPs, offsetting gains can be expected from standardization, simplification, passive safety, lower radionuclide inventories, factory fabrication, fast installation, and low financing costs (Liou 2021). Additionally, most developers envision multi-reactor deployments which would mitigate diseconomies by having common services and distribution.

Regarding standardization, the *Quality Assurance Requirements for Nuclear Facility Applications* (ASME NQA-1 2022) recognizes simplicity of design, the degree of standardization, and the similarity to previously proved designs as having low risk compared to complex, state of the art (first of a kind or FOAK) applications. Further, the limited scale of an SMR limits the financial risks to investors such as utility companies and their subscribers.

So, a reduced level of risk is needed to accelerate subscribers to nuclear energy. An aggressive transition to clean energy is underway to head off predicted increases in global temperatures. The Intergovernmental Panel on Climate Change (IPCC) and many others have identified nuclear energy as an important part of a portfolio of non-carbon energy sources. However, build rates in the hundreds of microreactors by 2040 and thousands by 2050 (Shropshire 2021) are needed to make a significant difference in global temperatures.

However, the deployment of a large number of units in a short period of time requires the mobilization of existing commercial forces who normally build housing, hospitals, and roads and bridges. This paper proposes a pathway for the transition of these forces to builders of nuclear facilities.

Nuclear Economics

Cost models for nuclear cost components have been developed and refined several times over the past few years. The original model was based on data collected from large, legacy power plants. Newer models attempt to estimate the cost of small modular reactors and microreactors (Hoffman 2020, Abou-Jaoude 2021, and Shropshire 2022).

A more recent report from INL (Abou-Jaoude 2021) proposes an approach that emphasizes economic considerations such as market drivers ahead of the design process as depicted in Figure 1. Design parameters and technical specifications are systematically evaluated until costs meet the market entry point. For the sake of efficiency, no effort is expended on a design when there is no market for the product. The Design Bais Model described in the report fits in this approach as illustrated in Figure 1.

This paper proposes the use of standard construction conventions and a standard product line (INCOSE 2023c). to create a Design Basis Model for hosting SMRs and microreactors. For this purpose, a model is a database and the software needed to simulate the end-to-end development of a complex system, consistent with the left-hand side of the Systems Engineering Vee model (INCOSE 2023a).

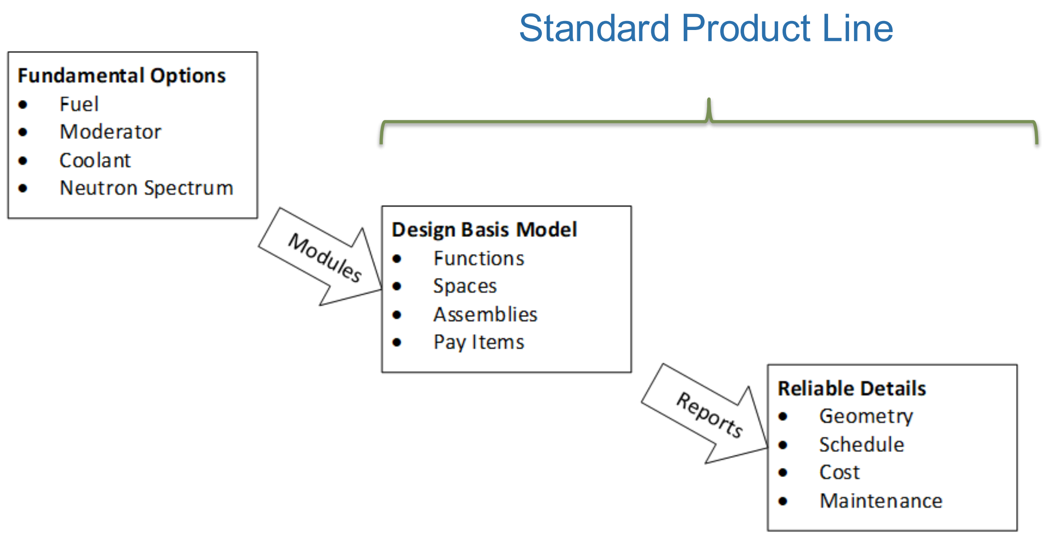

Figure 1. The Design Basis Model in the Economics by Design Approach

The Design Basis Model

Perhaps the most misleading notion for system development, nuclear or otherwise, is that it can be modeled as a so-called "waterfall" timeline. The notion translates to a project schedule where Task A on line 1 of the schedule finishes and then Task B on line 2 commences. Some projects will unlink the finish to start relationships to decrease product development time and the time to market, leading to "improved" productivity and reduced costs.

However, a premature jump into design and development can be very costly as realized in Figure 2 below (INCOSE 2023a). The author has seen this happen while working on several projects. Projections of nuclear plant costs have repeatedly failed to predict the cost overruns observed since the 1960s (Eash-Gates, 2020).

In practice, system development is a highly iterative process as depicted in the Systems Engineering Vee model developed in the 1990s and widely referenced ever since then (INCOSE 2023a). The Vee model developed at INL for recent test bed development is shown in Figure 3 below. Emphasis is placed on the systematic approach toward functional and performance requirement decomposition. The strict adherence to the systems approach helps to verify that the requirement set is complete and will result in a complete set of functional tests required to establish confidence in the safety and operability of the system. Other characteristics of good requirement sets are met in accordance with INCOSE 2023b.

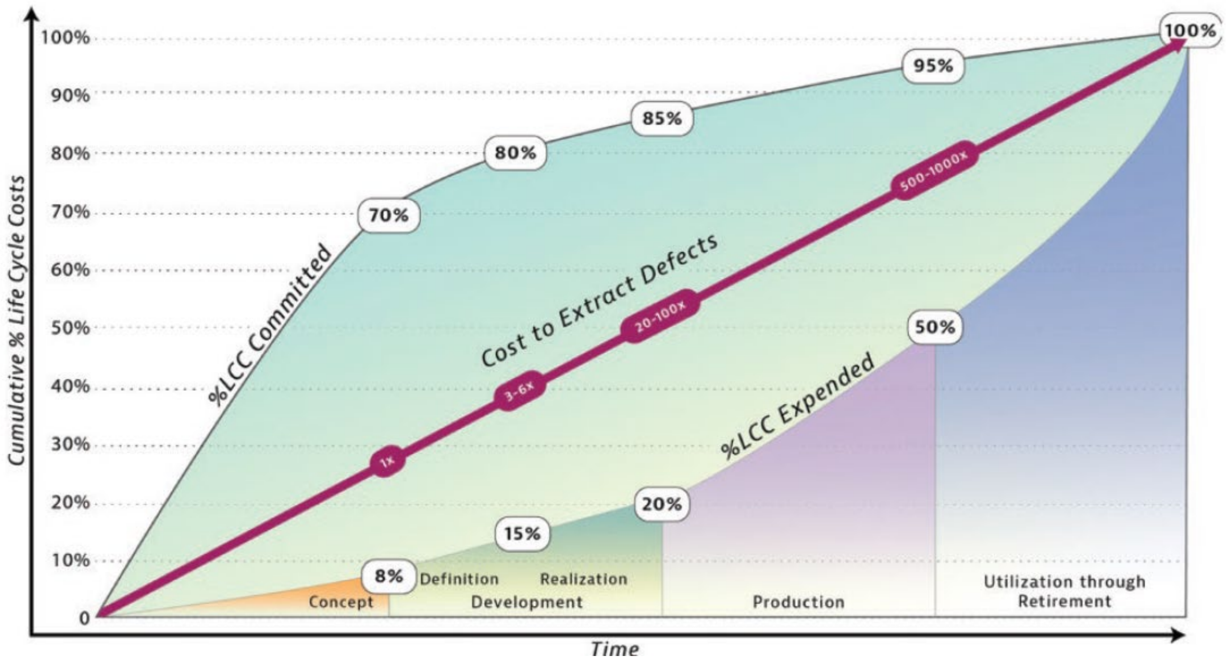

Figure 2. Cost of Design Changes as a Function of System Development (INCOSE 2023a)

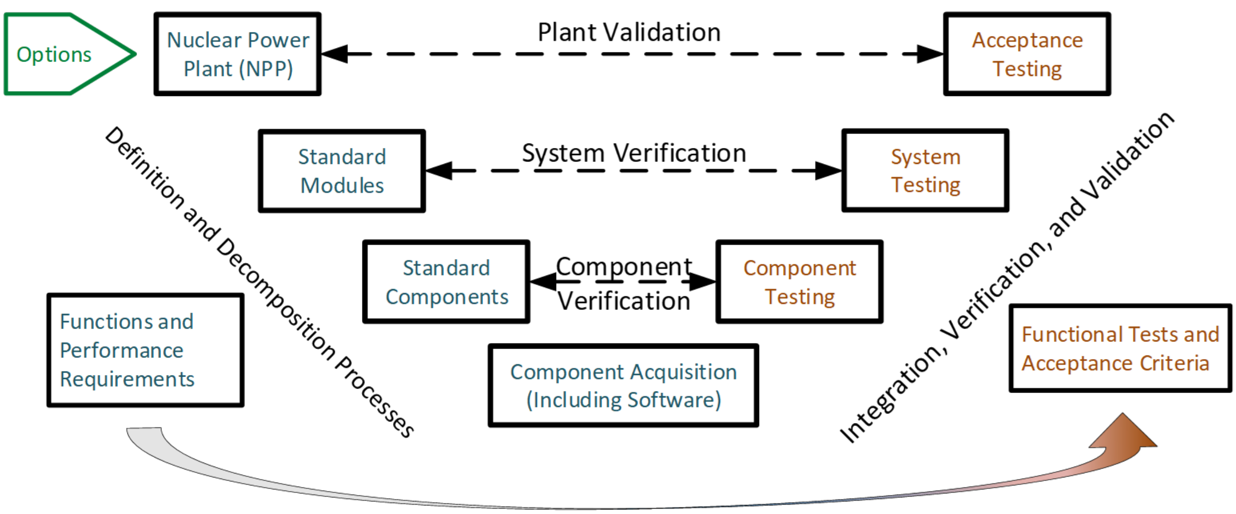

Figure 3. Decomposition to Standard Modules and Components

To speed iteration at the earliest point in the project, the concept that is developed ahead of the requirement decomposition should be informed by a trade study consistent with the economics by design approach shown in Figure 1 above. Still, the marketability of a product is not fully discernable without design details to evaluate system "ilities" typically associated with trade studies (McManus 2007). In this case, the "ilities" for SMRs and microreactors are adapted from by Abou-Jaoude 2021:

- Reliability – uninterrupted access to electricity (especially important in extreme climates)
- Serviceability – local, rapid repairs/maintenance
- Operability – avoiding reliance on highly skilled operators/staff
- Constructability – shorter timelines drive cost and risk reductions

- End user compatibility – proximity to end users engenders noise requirements
- Environmental compatibility – limited damage to nature (including pollution) during construction and operation
- Transportability – by truck, sea, or air (when road infrastructure is minimal)
- Securability – protecting assets within the site perimeter
- Predictability – schedule shipments (e.g., fuel) during periods of favorable weather conditions
- Durability – resiliency against challenging climate conditions throughout the year
- Affordability – competitive cost of electricity production.

The Classification System

Every model requires a classification scheme. Developing a classification scheme from scratch is a time-consuming, iterative process much like the decomposition process using the Systems Engineering Vee model. This process generally results in a classification scheme that is unique – a scheme developed by one organization likely differs from classification schemes derived by others.

The US-based construction industry typically uses some form of OmniClass for a classification system. Other countries may use a similar system called Uniclass (Afsari 2016). Similarly, the International Association of Oil & Gas Producers (IOGP) is developing the Capital Facilities Information Handover Specification (CFIHOS) to establish equipment naming taxonomy (IOGP 2023). The advantage of OmniClass is that it incorporates the standard Uniformat and MasterFormat numbering that is used world-wide.

Most architect/engineering (A/E) firms in the US are at least aware of the OmniClass classification system. Typical three-dimensional (3-D) software such as Autodesk Revit is oriented along this line (Autodesk 2023) as is the BIMForum (2023), RSMeans (2023 construction cost data), and popular construction specification libraries such MasterSpec (Deltek 2023) and SpecLink (RIB 2023).

Adapting commercial design and construction practices for the nuclear industry is an imperative to accelerate deployment of NPPs. As stated in the "Who We Are" web page (NRIC 2024), the National Reactor Innovation Center (NRIC) is a national Department of Energy program that accelerates the demonstration and deployment of advanced nuclear energy (such as SMRs and microreactors).

The NRIC Program is led by Idaho National Laboratory (INL) which has decades of experience at hosting small experimental reactors. The standards and the procedures in place at INL are mature interpretations of the laws. regulations, and U.S. Department of Energy (DOE) orders and standards that govern such activities.

An extensive analysis of the laws. regulations, DOE orders and DOE standards applicable to INL reactor projects (called the Code of Record) identified over 10,000 references to governmental and industry standards. Each of those references requires some sort of expert interpretation to determine applicability for a specific reactor project. So having that interpretation embedded in INL standards and procedures is a significant expedient to the development of projects for hosting experimental reactors.

Augmenting OmniClass for the nuclear industry is analogous to the "commercial grade dedication" process (NRC 2022) where commercially available parts, normally not qualified for nuclear use, are tested extensively for use as nuclear components. This is the default process when the nuclear supply chain is insufficient for some reason.

OmniClass has several tables applicable to NPP facilities:

- Table 11: **Entities by Function**. For example, the land and utilities provided by the site, access control gates, administrative buildings, control buildings, storage facilities, containment structures, maintenance facilities, etc. The OmniClass table doesn't have a full suite of these entities needed for a NPP, so this table must be augmented for the nuclear industry.

- Table 13: **Spaces by Function**. Office Spaces, Workstations, Service Spaces, Environmentally Controlled Spaces, Maintenance Spaces, Toilet Facilities, etc.
- Table 21: **Elements (UniFormat)**. Classifies subassemblies of major components such as substructure, shell, interiors, services, equipment, furnishings, special buildings, demolition, and sitework. Top-level numbering for this table is as follows:
    - A SUBSTRUCTURE
    - B SHELL
    - C INTERIORS
    - D SERVICES
    - E EQUIPMENT AND FURNISHINGS
    - F SPECIAL CONSTRUCTION AND DEMOLITION
    - G BUILDING SITEWORK
    - Z GENERAL
- Table 22: **Work Results (MasterFormat)**. These are construction specifications that define administrative and technical requirements for contractors for the purchase of products/components, installation, and testing of assemblies. Refer to the BIMForum Level of Development (LOD) Specification for examples of the relationship between UniFormat and MasterFormat.
- Table 23: **Products**. Components or assemblies of components for permanent incorporation into construction entities. These generally match up with the products identified in Part 2 of the 3-part construction specifications listed in Table 22.

The two tables that are missing from the set are sizing parameters and functions.

Regarding sizing parameters, the design basis for modular development begins with 3D models of the modular entities. A typical containment structure for nuclear operations would be a variation of the concept illustrated in Figure 4 below.

In this example, the isolation valves and everything required to actuate them are as important to safety as the containment structure. All other components shown are of lesser importance, so their requirements may be satisfied with commercially-available hardware.

Having the 3D models and the reactor in hand, the footprint for the module is established and is used along with other parameters such as thermal output per reactor, efficiencies, and cost estimates. These factors are then used to determine the number of modules needed to meet the required overall output of the NPP. Additional parameters for cost estimates are enumerated in Abou-Jaoude (2021).

Regarding functions, a functional analysis for various types of reactors and their modules is required to establish a comprehensive table for this Design Basis Model. This effort serves other purposes such as the entry point in the middle-out approach to requirement decomposition. A requirement set is not complete until performance requirements are derived for each function. Additionally, functional analysis is the entry point for in a Value Engineering Study.

There are several ways to perform a functional analysis but the most comprehensive and most expedient (in the author's experience) is the Functional Analysis System Technique (FAST) (INCOSE 2023a, 4th Ed).

The FAST process is comprehensive in that it doesn't require a flow diagram. Many functions in a process such as "Supply X" and "Contain Y" are done concurrently so a flow diagram is not a good fit for those functions.

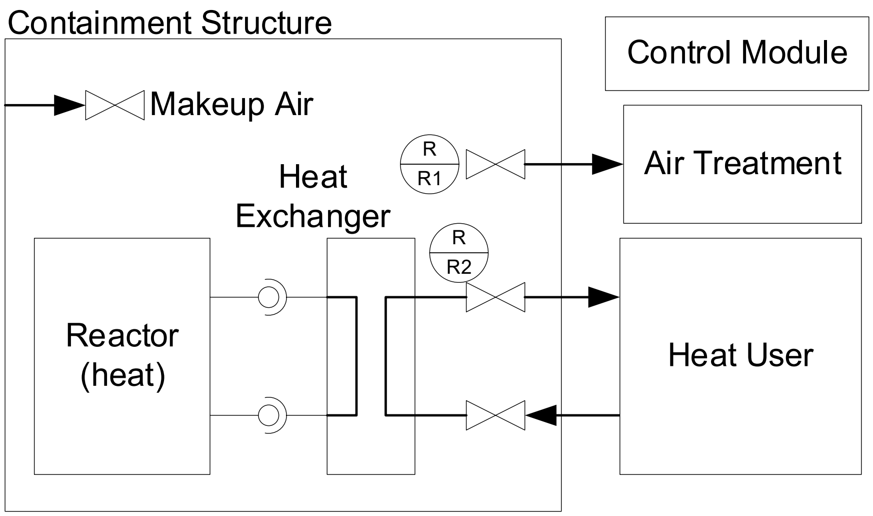

Figure 4. Typical Arrangement of Modules Hosting an SMR

Notes for Figure 4:

1. Each reactor from the factory requires a containment structure that is designed to withstand the heat from an operating reactor and dissipate the remaining heat after the reactor is shut down.
2. The containment structure is also designed with minimal fissures to prevent an airborne release to the environment. The air treatment module draws air through the structure to create a negative pressure needed to direct any in-leakage into the air treatment module.
3. Similarly, the structure is built to contain all the liquids that may be spilled from the operations within.
4. The heat exchangers within the containment structure provide isolation between the primary loop out of the reactor and heat users.
5. Each fluid penetration of the containment structure is equipped with an isolation valve:
   - If radiation is detected in the air exhausted to the air treatment module, airflow to the module is shut down and the isolation valve is closed.
   - If radiation is detected in the fluid on the user side of the heat exchanger, flow to the exchanger is shut down and the associated isolation valves are closed.
6. Upon shutdown, the reactor is disconnected from its infrastructure using remotely-operated telemanipulators. The disconnected reactor is removed from containment, placed in a cask, and transported elsewhere for further cooling and disposition of the fuel.

The FAST approach is also amenable to self-checking. Functions at Level N+1 define how the function at Level 1 is performed. Therefore, the function at Level N explains why the functions at Level N+1 are needed. The functional decomposition is correct when each function can be described in a cogent sentence consisting of the following pattern: The <actor>shall<function name>to<why> where the:

Actor: Is either the Project (construction) or the Module (post-construction)

Name: Is a verb-noun combination for constructing the cogent sentence

For example, if the function at Level N is "Protect Personnel, Material, and Equipment". One of the functions at Level N+1 (a "how" function) might be: "Suppress Fire". Therefore, the description would be "The <Module> shall <Suppress Fire> to <Protect Personnel, Material, and Equipment>. The clarity of the resulting sentence confirms that the named functions are correct and in the correct position in the decomposition hierarchy.

OmniClass Table Relationships

Adding links to lists such as those provided by the OmniClass tables is a force multiplier. Lists with links enable iteration and recursion as described in INCOSE 2023a. Lists with links are also the heart of the MBSE approach since all MBSE diagrams are eventually converted to tables and coding logic.

The associations for the Design Basis Model are illustrated in Figure 5 below using SysML syntax. The base table for the Design Basis Model is an extension of OmniClass Table 11, Entities by Function. The extension of this and other tables in OmniClass is required to include the unique modules needed for an NPP.

The **functions** derived above, the individual items in the OmniClass Table 13, Spaces, and items from OmniClass Table 21, Elements (UniFormat) are then allocated to each of the named entities.

As is done in the Level of Development (LOD) Specification (BIMForum 2023), items in OmniClass Table 22, Work Results, are assigned to each of the items in OmniClass Table 21, Elements (UniFormat). To establish a credible cost estimate for module, Table 21 elements are further specified in terms of "pay items" for entry on schedule of quantities and prices (SOQP) or otherwise known as a Schedule of Values (SOV). These "pay items" are construction cost estimates in terms of sizes, labor, overhead, and profit. A good example of these pay items is provided in Cost Data Books (RSMeans 2023).

With all these links in place, an end-to-end design basis and cost estimate can then be assembled automatically using iteration and recursion.

Using the links to OmniClass Table 21, Elements (UniFormat), a series of design basis reports (or document sections) can be assembled automatically with these headings:

- Architectural Basis of Design
- Structural Basis of Design
- Services Basis of Design
- Sitework Basis of Design

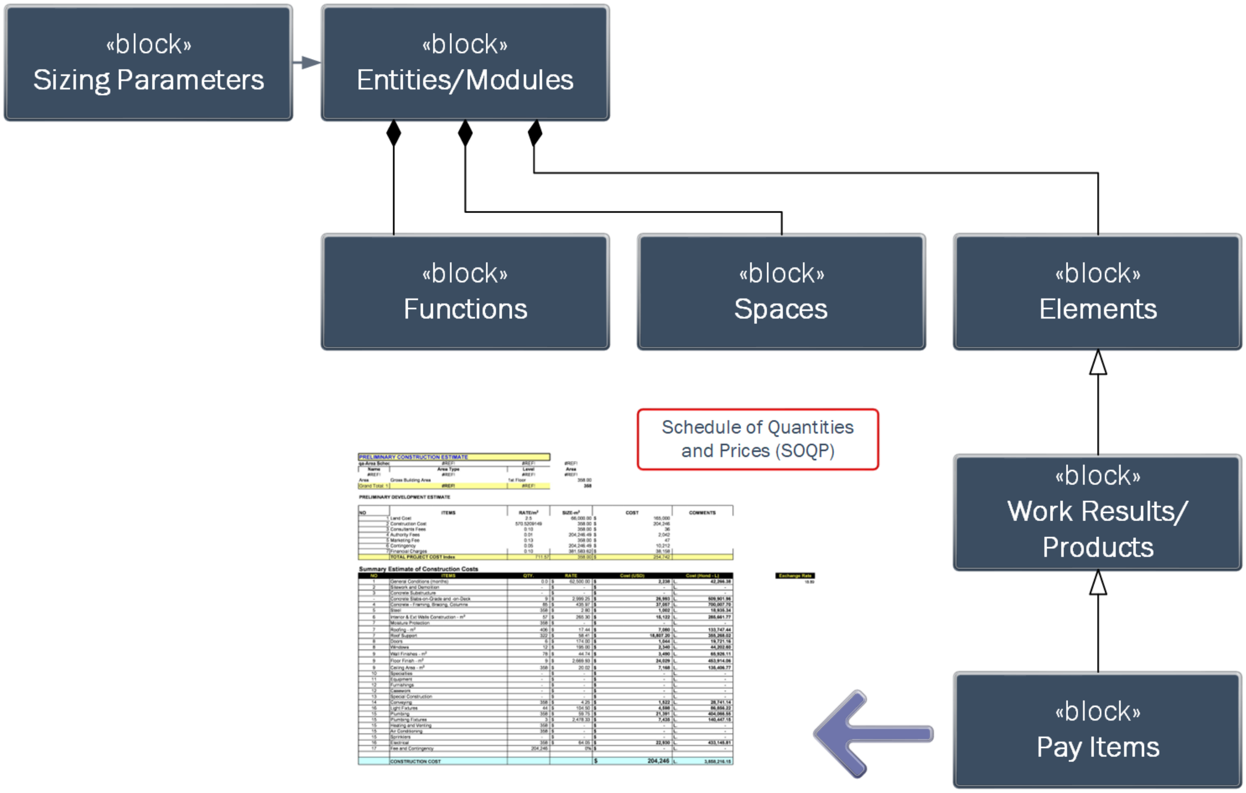

Figure 5. Table Associations Created for the Design Basis Model

Each report or section would then have these major headings.

1. **Modules**: Significant, definable units of the Project comprised of interrelated spaces and elements and characterized by function.

2. **Parameters**: Quantitative parameters used to size each Module.

3. **Functions**: Functions associated with each Module as defined by users and other stakeholders.

4. **Spaces**: Basic units of the Module delineated by physical or abstract boundaries and characterized by their function or primary use.

5. **Elements**: A major component, or assembly with UniFormat numbering that fulfills a predominating function of the Module. Predominating functions include, but are not limited to, supporting, enclosing, servicing, and equipping a module.

6. **Pay Items**: Descriptions for line Items in cost estimates, schedule of quantities, work results, and invoices. The base numbering for this section is MasterFormat specification section numbers with additional numbering for variations such as material of construction and sizes.

While the contents of these reports are very terse, the DOE has a similar set of documents called System Design Descriptions (SDDs) with content expressed in paragraphs, tables, and figures spread over four Chapters:

1. **System Identification**: Identifies the scope of each module.
2. **System Functions**: Functionality of each module as derived from the functional analysis.
3. **System Requirements**: How well each function is performed (Performance Requirements)
4. **System Description**: Objective evidence regarding how each requirement is met.

As is done for design basis documents, SDDs are drafted using lists and links collected from INL standards and procedures.

A library of standard constructions specifications is also developed from these sources using natural language processing (NLP) techniques to streamline requirements consistent with modern practices for construction projects (Claghorn and Shubayli 2021).

Additionally, current projects underway at INL provide data that can be collected for an SMR Cost Data Table to extend commercial cost data books.

Building Information Management

The *Level of Development (LOD) Specification for Building Information Models* (BIMForum 2023) defines Level of Development (LOD) as the degree to which the element's geometry has been thought out – the degree to which project team members may rely on the information when using the model. Four of the LOD levels are defined as follows:

- LOD 100: The Model Element may be graphically represented in the Model with a symbol or other generic representation but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, tonnage of air conditioning, etc.) can be derived from other Model Elements.
- LOD 200: The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element.
- LOD 300: The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. The BIMForum interpretation is that the quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs.
- LOD 400: The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information.

Given the reuse of a standard, modular design, coupled with standard design and construction practices, the Design Basis Model described in this paper could be classed as LOD 300. Additional details for the specific project are required to progress the design beyond LOD 300.

The Design Basis Model described in this paper may also be used as a basis for each of the Building Information Modeling (BIM) dimensions – 3D, 4D, 5D, 6D & 7D as defined below (United BIM 2023).

Table 1. BIM Dimensions

Dimension	Quantity	Output
3D	Geometry	3-dimensional (x, y, z) geographical structure.
4D	Time	Timeline, scheduling, and duration
5D	Money	Cost estimation, budget analysis
6D	Sustainability	Self-Sustainable & Energy Efficient
7D	Maintainability	Facility (Asset) Management Information

BIM 3D, the built geometry, is approximated using the 3D models of the modular units that underpin the Design Basis Model. Arranging these units at the site location identifies the footprint required for the NPP and the excavations needed for each of the modules.

BIM 4D, the construction timeline, is approximated by slight rearrangement of the items identified in OmniClass Table 21, Elements, otherwise known as UniFormat. Figure 6 below illustrates this rearrangement.

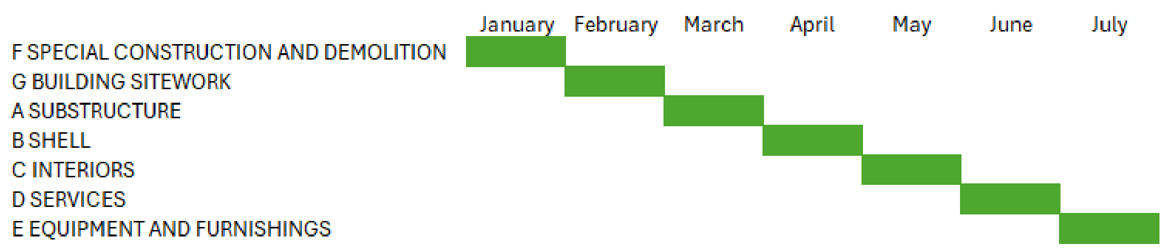

Figure 6. Using UniFormat to Approximate a Construction Schedule

BIM 5D, the cost estimate, is approximated using a rollup of the pay items identified in the Schedule of Quantities and Prices (SOQP). The pay items are associated with the products identified in Part 2 of the construction specifications which are numbered in accordance with OmniClass Table 22, Work Results, otherwise known as MasterFormat.

BIM 6D, energy efficiency, is achieved using well-worked standards and energy modeling for each of the modules. The containment structure is unique in that it would be designed to dissipate heat upon reactor shutdown.

BIM 7D, maintainability, may be estimated from commercial data tables for each of the module components identified in BIM 5D.

Conclusions

To provide energy security and head off further increases in global temperatures, an aggressive transition from fossil fuels to other types of energy implies the need to possibly construct hundreds of nuclear power plants in the near future. However, the real and perceived risks of nuclear energy remain a significant impediment to this transition. Reducing these risks is imperative to accelerate deployment of NPPs.

The National Reactor Innovation Center (NRIC) is a national Department of Energy program that accelerates the demonstration and deployment of advanced nuclear energy such as SMRs and microreactors. The NRIC Program is led by Idaho National Laboratory (INL) which has decades of experience at hosting small experimental reactors. That experience can be used as a significant expedient to the development of SMRs and microreactors.

In addition to research and development activities at INL, the NRIC is refurbishing existing facilities as test beds to host microreactors developed by commercial entities. The INL lends its expertise to these entities to ensure that the proposed reactors meet all the safety requirements required of a commercial reactor.

The test beds at INL are designed to host multiple types of reactors. This capability demonstrates the feasibility of developing standard, model-based designs for hosting small modular reactors. The application of mature models as the design basis for NPPs increases the production, reproducibility, and reliability of construction documentation, project schedules, and cost estimates.

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Biography

Ronald (Ron) Claghorn. Career modeler. As a Systems Engineer, I develop, verify, and validate requirements using automation and structured data for small to billion-dollar projects. I have developed and presented trade studies that underpin major design decisions. I have developed Concept of Operations, design bases, system design descriptions, and specifications for the nuclear industry at the Idaho National Laboratory (USA), nuclear waste disposition at the Hanford Nuclear Reservation (USA), and for the industrial cities of Saudi Arabia.