Advanced Tools for Advanced Reactors

Why Computer Codes Are Essential to Ensuring Access to a Clean, Reliable, and Sufficient Energy Supply

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The purpose of computing is insight, not numbers.

- Richard Hamming

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Executive Summary

As the world's concerns regarding climate change continue to intensify, society is looking for energy solutions that can provide enough low-carbon energy to support not only current global power needs but also the energy needs of countries that are on the verge of societal expansion. Nuclear energy is a source of carbon-free energy production that is sufficient, reliable, and sustainable, and it can be a solution to these low-carbon energy shortage issues. Nuclear power can be deployed independently, or it can be utilized to supplement inconsistent renewable sources of energy like solar and wind (e.g., when it is nighttime at a solar plant). Regardless of how it is implemented, the use of nuclear energy is essential to reaching society's low-carbon energy production goals.

Alongside the increased distress surrounding climate change and our global carbon-free energy supply, the nuclear power industry is experiencing a technological renaissance. Advanced nuclear reactors are a significant departure in design from the current light water reactors (LWRs), which are the only power plant technology utilized for commercial electricity production in the United States today. Advanced nuclear reactors boast significant potential benefits over traditional LWRs, and their designs have started to gain newfound legitimacy and traction in the past decade. As a result, the United States Nuclear Regulatory Commission (NRC) has set forth a plan to modernize its regulatory framework to effectively license them to operate commercially.

This decision to modernize is a result, in part, of a common complaint the NRC has received regarding their current regulatory framework. This criticism is that their licensing processes are "prescribed" to the older, larger, LWRs that have been the source of most of the United States' nuclear power since it started splitting atoms to generate electricity in the latter half of the twentieth century. And as advanced reactor designers depart from the large, centralized power plant designs of old and instead choose to pursue more dynamic, smaller, and diverse reactor technologies, they have prompted the NRC to become a more dynamic regulator as well.

The NRC was officially prompted to develop Part 53 of the Title 10 Code of Federal Regulations (10 CFR Part 53), a new technologically inclusive licensing framework, by the enaction of the Nuclear Energy Innovation and Modernization Act in 2019. Developing a new framework entails a wave of policy, structural, and regulatory changes within the NRC. These intra-agency modifications have not failed to include the modeling and simulation (M&S) tools the NRC uses to evaluate the safety of nuclear power plants. On the contrary, the NRC has initiated an overhaul of its M&S analytical tools, tools that have always been central to the regulatory process.

Modeling and simulation is integral in licensing reactors because it allows for applicants to demonstrate the safety of their power plants without performing expensive, time-consuming experiments. M&S also provides the NRC with the ability to verify a design's safety by allowing licensing reviewers to assess the applicant's plant safety analysis with high accuracy. There have

also been recent advancements in M&S's ability to provide crucial insight into reactor and plant processes; insight that could not be gained otherwise without expensive and time-consuming experimentation. Thus, the NRC must utilize these new M&S methods to evaluate reactors as accurately as possible. This will ensure the determination of adequate safety margins that are not too conservative, which will allow the potential benefits of advanced non-LWRs to be maximized.

The NRC has introduced policies that address M&S's role in the licensing of advanced non-LWRs. It has also introduced policies that identify how the NRC plans to update its M&S capabilities to ensure their readiness to evaluate advanced reactors. In this paper, these newly introduced policies are analyzed, and policy recommendations are provided that can ensure M&S not only remains integral to the licensing process but that the analytical tools employed are adequate.

It is determined that the NRC's policy efforts to keep M&S central to the licensing process and to update its M&S capabilities to handle non-LWRs have been sufficient thus far, but there are still some concerns that need to be addressed. It is well known among computational engineers that analytical models must be validated with experimental data that represents the physical phenomena being simulated. Nevertheless, the NRC has publicly expressed that there is a need in this area for the codes they plan to use to analyze non-LWR reactor designs. However, there is not a systematic policy approach that has been developed to address these experimental data gaps. Therefore, recommendations for how to secure funding to perform experiments to obtain these crucial data are provided.

In summary, the recommendations will prompt the NRC to develop an unprecedented collaboration with the DOE to ensure this crucial validation data is obtained. If these recommendations are followed, then the NRC will surely be steps closer to ensuring their analytical M&S tools are as effective as possible, which is vital to accurately evaluate the safety of nuclear reactor designs, and ultimately provide clean, reliable energy for the entire nation.

Preface

About the Author

Robby Renfrow recently graduated in May 2021 from Lipscomb University in Nashville, TN where he obtained a B.S. in Mechanical Engineering. His activities at Lipscomb included participation in ASME, ANS, Lipscomb Engineering Honor Society, humanitarian engineering trips to Central America, and being a teaching assistant for multiple courses. During his junior year, he became interested in nuclear energy when he learned of its potentials as a reliable, sustainable, and low-carbon energy source. These interests have led him to obtain sponsorship from ANS for the WISE Program and have even led him to pursue a Ph.D. in nuclear engineering, a journey he will begin this fall at the University of Michigan researching advanced modeling and simulation methods for nuclear reactors under Dr. Won Sik Yang.

About the WISE Program

The Washington Internship for Students of Engineering (WISE) program was founded in 1980 through the collaborative efforts of various professional engineering societies. During its successful run, this program has become one of the premier Washington internship programs. Each summer, participating societies select exemplarily students in engineering or computer science programs who are nearing completion of their undergraduate degree or are recent graduates. These students are selected from a national applicant pool and work closely with their sponsoring society during the nine-week program. By gaining exposure to policymaking through leaders in the Federal government, students are responsible for researching, writing, and presenting a paper on a topic pertinent to their sponsoring society. For more information about the WISE program, visit www.wise-intern.org.

About ANS

The American Nuclear Society (ANS) is the premier organization for those that embrace the nuclear sciences and technologies for their vital contributions to improving people's lives and preserving the planet. ANS membership is open to all and consists of individuals from all walks of life, including engineers, doctors, students, educators, scientists, soldiers, advocates, government employees, and others. Celebrating its 70th anniversary in 2024, ANS is committed to advancing, fostering, and promoting the development and application of nuclear sciences and technologies to benefit society.

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Acronyms

ACRS	Advisory Committee on Reactor Safeguards
AEC	Atomic Energy Commission
BWR	Boiling Water Reactor
CFR	Code of Federal Regulations
COL	Combined License
COLA	Combined License Application
CP	Construction Permit
CRAB	Comprehensive Reactor Analysis Bundle
DC	Design Certification
DID	Defense-in-Depth
DOE	Department of Energy
ERDA	Energy Research and Development Agency
ESP	Early Site Permit
FSAR	Final Safety Analysis Report
FSV	Fort St. Vrain
GAIN	Gateway for Advanced Innovation in Nuclear
GDC	General Design Criteria
HPC	High-Performance Computing
HTRG	High-Temperature Gas-Cooled Reactor
ITAAC	Inspections, Tests, Analyses, and Acceptance Criteria
LBDP	Licensing Basis Development Process
LBE	Licensing Basis Events
LMFR	Liquid Metal-Cooled Fast Reactor
LMP	Licensing Modernization Project
LWR	Light Water Reactor
MSCR	Molten Salt Cooled Reactor
MSFR	Molten Salt Fueled Reactor
MSR	Molten Salt Reactor
NE	Office of Nuclear Energy
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NEET	Nuclear Energy Enabling Technologies
NEI	Nuclear Energy Institute
NEIMA	Nuclear Energy Innovation and Modernization Act
NEUP	Nuclear Energy University Program
NPP	Nuclear Power Plant
NRC	United States Nuclear Regulatory Commission
OL	Operating License
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
SAR	Safety Analysis Reactor
SFR	Sodium-Cooled Fast Reactor

SMR	Small Modular Reactor
SSC	Structures, Systems, and Components
TI-RIPB	Technology Inclusive, Risk-Informed, Performance-Based
TRISO	Tri-structural Isotropic
VHTR	Very High-Temperature Reactor
VS	NRC Vision and Strategy Document

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1. Introduction

Nuclear power is commonly disregarded from consideration as a low-carbon energy source. However, its production of electricity is completely carbon-free, and it is more reliable and consistent than renewable energy sources like solar and wind. With society's increased concern surrounding climate change and the shortage of low-carbon energy, and as the world continues to search for carbon-free energy solutions, nuclear energy needs to be included in the equation. Nuclear power can be deployed independently, or it can be utilized to supplement inconsistent renewable sources of energy like solar and wind (i.e., when it is nighttime at a solar plant). Regardless of how it is implemented, the use of nuclear energy is essential to reaching society's low-carbon energy production goals.

Today, the nuclear industry looks far different than it did when it began in the early second half of the twentieth century. In the 1950s, the government coordinated multiple efforts at national labs that were experimenting with many different reactor configurations. Many of the "advanced" reactors that are emerging today employ technologies that were being tested by national laboratories across the country during this time. The question of why non-LWRs are not employed in this country today does not have a clear answer. However, impediments that existed like material limits, unexpected implementation issues, etc. have been largely overcome by non-LWR developers in recent years. Now, with the growing familiarity with the implementation of this technology, coupled with a growing public realization of a need for reliable, low-carbon energy, several companies have emerged with advanced reactor designs that have a legitimate chance of becoming licensed and generating sustainable power.

However, since this lack of technological and operational expertise was present in the genesis of the commercial nuclear industry, a configuration that was feasible and well understood was chosen, standardized[*], and championed in the decades following up to the present day. These reactor designs are called "Light-Water Reactors" (LWRs), which reflects the use of water as their working coolant and moderator. LWRs make up all 93 nuclear plants that generate civilian power in the country today [1]. As the industry has evolved, these reactors have all become nominally[†] similar in design, with two main different variations: the Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR). This similarity has resulted in a licensing process originally developed by the Atomic Energy Commission (AEC) and built upon by its successor and current governing body, the U.S. Nuclear Regulatory Commission (NRC), that is prescribed specifically for LWRs. Generally, this prescriptive method has been somewhat effective at regulating nuclear power over the past few decades. However, it has come at the unintended cost of stifling innovation, which is one of the main roadblocks the industry faces today.

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[*] *Standardized*, as it is used here, refers to the general PWR and BWR technology. Almost all U.S. reactors were customized in some way, which caused problems in the licensing process.

[†] *Nominally* is used the same way as *standardized* is above.

This roadblock exists at a time when operating reactors are going offline and new plants are not being built to compensate for the sustainable nuclear power that has been lost, whether it be because of licensing issues or otherwise. This issue is especially urgent as the public push for carbon-free, reliable energy increases amidst the growing concerns about climate change and the low-carbon energy shortage. Advanced reactor technology offers solutions to these issues while also addressing the concerns many people face when it comes to nuclear. Advanced reactor developers boast potential characteristics like passive safety features, lower waste volumes, and higher economic efficiency.

The barriers to the implementation of non-LWR technology have shifted from mainly scientific limitations to mainly political, economic, and social ones. Even though the NRC has claimed they “do not want to be an inhibitor, but an enabler” [2], the former is a more appropriate title at the present. Nevertheless, the NRC is trying to change this notion. With the enaction of the Nuclear Energy Innovation and Modernization Act (NEIMA) [3] in January 2019, the NRC has been directed by Congress to modernize its licensing process. This bill specifies that the framework of the new regulatory method must be “technology-inclusive” and “performance-based” rather than specific and prescriptive. The new, high-level regulations governing this process will be published in Title 10 of the Code of Federal Regulations (CFR), Part 53 (condensed to Part 53, coming after Parts 50 and 52, the current regulatory processes). Technology-specific details likely will be provided elsewhere in guidance documents.

The two main aspects of the old licensure process are the technical design requirements and procedural requirements that must be met for the plant to be licensed. For Part 53, it is not known yet how the procedural requirements will change since the NRC is still in the early stages of development. However, the technical requirements and how they will change is more well-known at this point. In this paper, the focus will be on the technical requirements and how those parameters should be evaluated to ensure Part 53 meets the NRC’s objectives of creating an efficient and inclusive licensing process.

To accomplish this, the NRC must, somewhat traditionally, continue to rely on its past methods of evaluating reactor technologies: with analytical modeling and simulation (M&S) tools. Starting in the 1960s, AEC or NRC licensing reviewers would verify that a plant design met the established safety requirements with computer models. However, these models were rather crude compared to modeling capabilities within nuclear engineering today. Thus, as computing power has substantially increased over time, so has the fidelity of the models. For example, in June 2021, a team of engineers simulated the entire core of a Small Modular Reactor (SMR) with high fidelity [4].

Therefore, it is obvious why M&S has also been at the core of nuclear energy innovation since it has enabled developers to save time and money by supplementing physical experimentation. Advanced M&S can also provide crucial insight into reactor processes, which allows safety margins to be properly set. This has not always been the case, though, due to the relative crudeness of the models that were being used in the early days of nuclear regulation and the uncertainties associated with them. Since these models had high uncertainties, adequate safety margins could not be set and were usually assumed to be large, which ended up constraining the technology and did not allow for a proper technical evaluation of the design.

Regardless of the relative capabilities, computing has always been at the core of reactor regulation, and the NRC should not depart from this tradition now. Thus, ensuring the regulators have access to adequate M&S tools is vital to modernizing the nuclear industry and effectively utilizing advanced nuclear as a low-carbon energy source, for a technology is only as advanced as its governing regulatory body.

As the NRC has undertaken this effort to modernize the licensing process and make it more inclusive, it has also made plans to modernize its M&S capabilities. This generalized, performance-based, risk-informed approach will call for and has already caused an overhaul of the computer codes being utilized by the NRC. Thus, the purpose of this report is to independently investigate and evaluate the NRC's policies involving M&S amidst licensing modernization and Part 53 development, along with how the NRC plans to use M&S to inform the policy decisions it will make involving reactor licensing. Alongside this investigation, concerns about the future of M&S development and policy recommendations for how to address these concerns are presented.

2. Background

2.1 The NRC

2.1.1 History

Before discussing the NRC and its policies towards modeling and simulation, a history of the NRC must be provided for context. After World War II and the culmination of the Manhattan Project, nuclear energy and nuclear science were still completely regulated and maintained by the United States Government. This meant there was no private sector or commercial opportunity within nuclear energy. This was the case until the Atomic Energy Act [5] was enacted in 1954, which paved the way for the development of a commercial nuclear power industry.

The Atomic Energy Act established the regulatory agency, the Atomic Energy Commission (AEC), to oversee both the developmental side and the regulatory side of the industry. However, after twenty years, the agency's ability to tackle both areas was deemed inadequate, and the AEC was abolished by Congress due to the intense scrutiny it had faced [6]. In 1974, the Energy Reorganization Act was passed, which established the Nuclear Regulatory Commission (NRC) as the independent agency responsible for regulating all commercial nuclear activity [7]. The developmental half was assigned to the Energy Research and Development Agency (ERDA), later replaced by the current organization (DOE), which promotes a wide range of energy technologies.

2.1.2 Purpose

Since 1975, the NRC's mission has been to "license and regulate the Nation's civilian use of radioactive materials to provide *reasonable assurance* of *adequate protection*[*] of public health and safety and to promote the common defense and security and to protect the environment" [8]. However, this mission communicates that the NRC's utmost priority is the protection of the public and the environment from the unintended release of radiation. This means they regulate a wide breadth of industries within nuclear science—not just power reactors. Over the decades of nuclear regulation in the United States, it has proven difficult to regulate and license power reactors in a way that does not take relatively large amounts of time and restrict the implementation of new technology.

2.2 Current Licensing Methods

In addition to providing a background on the history and purpose of the NRC, it is important to understand NRC's process of ensuring a plant design meets the necessary technical requirements. Thus, a brief overview of the NRC's current licensure process will be presented here. Also, an overview of these processes should provide insight into why Part 53 is being created and why M&S needs to remain a crucial aspect of regulation.

If a vendor wants to implement their plant design to commercially produce electricity, then they usually must collaborate with a utility or a group of utilities in a specific region[†]. For example, if TerraPower wants to place their reactor outside of Seattle to generate carbon-free energy for the city, they must coordinate with a Seattle utility company to do so. Once the utility company is identified, the utility company can submit a license application, and the vendor will work as a contractor for the utility. After the plant is licensed, the utility company can load fuel, operate, and produce electricity. There are two existing methods for licensing a nuclear power plant (NPP) that have been established, which are specified in 10 CFR Part 50 and Part 52; however, they were not established simultaneously. Each of their courses will be briefly outlined below.

2.2.1 Part 50 [9]

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[*] The meanings of the terms "reasonable assurance" and "adequate protection" have caused much debate since they were first published and will not be discussed here since it is outside of the scope of this paper.

[†] Collaborating with a utility or group of utilities is not a requirement.

The first review process that was developed is described in 10 CFR Part 50 and is entitled, “Domestic licensing of production and utilization facilities”. Part 50 has been coined the “two-step” path for reasons that will be explained here.

First, after developing a power plant design and (usually) partnering with a utility company, the applicant (the utility company) must apply for a Construction Permit (CP). This permit, as its name suggests, gives the utility the authority to begin the construction of the power plant at the approved site. To obtain a CP, the applicant must submit a Preliminary Safety Analysis Report (PSAR), which, “discusses various hypothetical accident situations and the safety features of the plant that would prevent accidents or lessen their effects.” The PSAR does not necessarily include a comprehensive plan for the reactor, but it is supposed to present enough analysis to prove the design’s safety. These safety analyses are usually conducted by computer codes and have been since the 1960s [10]. However, as mentioned earlier, these first models were rather crude, but they were still integral to the safety verification process.

The NRC first evaluates the application to determine if it is sufficiently complete to begin a detailed review. If the application is accepted, then it is reviewed in detail by the NRC. Characteristics that are evaluated, as stated by the NRC, are as follows:

- characteristics of the site, including surrounding population, seismology, meteorology, geology, and hydrology
- design of the nuclear plant
- anticipated response of the plant to hypothetical accidents
- plant operations, including the applicant's technical qualifications to operate the plant
- discharges from the plant into the environment (i.e., radiological effluents)
- emergency plans

Once the review is complete and has received necessary internal approvals, the NRC also conducts an environmental review to ensure proper protection of the surrounding areas where the plant will be constructed. The public can comment on the reviews, and all the comments are addressed.

A public hearing is then held before the CP is issued to engage the public and their potential concerns. After the hearing and all concerns are properly addressed, a CP is granted, and the plant can be constructed. Once construction is complete, the applicant must obtain an Operating License (OL) before it can load fuel and generate power. To do this, the applicant is required to submit a Final Safety Analysis Report (FSAR) along with other supporting documents. Following the review of the FSAR and other application materials, a second public hearing is held. Assuming the hearing determines that the plant can be operated safely, the applicant is granted an OL and can load fuel and operate the reactor.

The requirement to receive a CP and then an OL after construction is why Part 50 is termed a “two-step” process. In the 1980s, the industry had realized that this method caused many delays, and it also required the applicant to put money at risk. For example, a plant could theoretically be constructed and not be granted an operating license. Another risk related to the “two-step” process was that the process would become drawn out if an OL could not be received immediately after the construction of the plant, which could cause an unexpected loss of large amounts of time and money. Thus, there was also a concern that this could lead to an applicant withdrawing altogether, which would be a waste of the NRC's resources as well. To combat this, the NRC tackled developing a new licensing process that was only “one” step: Part 52.

2.2.2 Part 52 [9]

The second, one-step licensing process that was developed is described in 10 CFR Part 52 and is entitled, “Licenses, certifications, and approvals for nuclear power plants." As stated above, this review process was created to be a more streamlined counterpart to Part 50. However, the technical requirements essentially remained the same.

As has already been mentioned above, the main difference between Part 52 and its predecessor is its “one-step” licensing procedure. Instead of receiving a CP and then an OL once the plant is constructed, an alternative, single license is granted—a combined license (COL). To obtain a COL, the applicant develops a full, high-fidelity plan for the powerplant and submits it to the NRC as a combined license application (COLA). Within the COLA is an evaluation of the plant’s safety and operational integrity as part of the FSAR, which is once again done with computer codes, just like the SARs in Part 50. The COLA is very similar to an application for an OL, except the submittal will contain more detail about the entire plant since the plant will be constructed and operated based on the COLA; whereas, under Part 50, the design is not cemented as heavily since an OL has not been received.

Part 52 also contains provisions for the approval of a plant design and/or the site for an NPP separate from a COLA. These provisions are called a standard design certification and an early site permit, respectively. The details of these processes are beyond the scope of this paper; however, they were established as part of the “streamlining” of the licensing process. The NRC encourages—but does not require--referencing a DC and/or an ESP as part of a COLA.

Even though the creation of Part 52 was intended to reduce the amount of financial risk associated with licensing, the plant may not load fuel into the reactor and generate electricity until it passes another round of inspections. During and after the plant is fully constructed, another review process called Inspections, Tests, Analyses, and Acceptance Criteria (ITAAC) must be performed. Some of these activities can be done as the plant is constructed, but some can only be done once it is built. Once the ITAACs are completed and completion is certified by the NRC, the applicant is permitted to load fuel and operate.

After investigating Part 52, one may observe that this "one-step" process is not truly one step. In fact, if one considers them significant, which they are, pursuing a DC and an ESP may even make it three steps (by this reasoning, ITAAC certification could even make it four steps). Also, Part 52 does not necessarily reduce fiscal risk. Its introduction was intended to reduce the amount of time and cost required under Part 50 to license and construct a plant. However, with Vogtle, the only plant that has received a COL under Part 52 and will likely be constructed, this has not been the case. The construction of Vogtle Units 3 and 4 has faced substantial challenges after receiving a COL in February 2012 [11]. These challenges include severe cost overruns and construction delays. With no established end date in sight, it can be said that the first-of-a-kind plant licensed under Part 52 has not relieved applicants of the high capital costs associated with plant licensing and construction. Another attempt may find more success, but that has not yet occurred. Thus, it could be argued that the NRC's efforts to streamline the licensing process made it more complicated in the long run.

These issues with Part 50 and Part 52, along with their prescriptive nature for LWRs shine light on why Part 53 is being developed. It should also be noted here that the current licensing framework caters to LWRs, and licensing LWR designs is still a struggle. Therefore, it is easy to imagine why it would be difficult for advanced non-LWRs to be licensed under the existing framework.

Regardless, it is important to note again that M&S has played crucial roles in the licensing process since the beginning of the days of the AEC. Even though they were relatively crude, for the applicant, analytical models were integral in generating supporting analyses in the Safety Analysis Report required under Part 50. Then, they were also crucial when the NRC would use their models to validate the ones utilized by the applicant in the SAR. This posture must remain as Part 53 is developed to ensure that reactors are safely licensed as efficiently as possible.

2.3 Part 50 Technical Requirement Issues

Similar to how it is necessary to gain a general understanding of the NRC's current regulatory process to understand why it is being modernized, it is important to investigate issues with the technical requirements as well. A description of the problems with the current technical requirements for nuclear plants imposed by the NRC will also give insight into why the NRC's technical staff needs to have access to adequate M&S analytical tools if they want to develop an inclusive framework and effectively evaluate NPP design safety.

2.3.1 Prescription to LWRs

As stated previously, the LWR-prescribed technical requirements (i.e., giving applicants specific instructions on how to design a reactor versus evaluating a reactor design based on performance) of Part 50 and Part 52 plant licensing are essentially the same. General technical requirements can be found in Appendix A of Part 50, which is titled the General Design Criteria (GDC), and more specific requirements are located within the regulations themselves. This prescriptive nature has caused problems because of their specificity to the technical design of LWRs that does not apply to non-LWR configurations. The NRC does state that these criteria are not required for non-LWRs, but there was never any design guidance developed for non-LWRs until Regulatory Guide 1.232 was published in 2018.

For example, if an applicant wants to license a new reactor design, say, a Sodium-Cooled Fast Reactor (SFR), until 2018 there was not design guidance available to give insight into what the NRC expected or desired in an application. Thus, a non-LWR applicant had to meet with the NRC before applying to determine the agency's expectations. Of course, there was not a need for this non-LWR design guidance before the past decade during which several non-LWR designs have shown they have the potential to pursue licensing soon. Regardless, without design guidance, it is difficult not only to efficiently evaluate license applications, but the lack of clarity also inhibits the applicant's ability to meet the NRC's requirements.

2.3.2 Regulatory Inconsistencies

Problems with the current Part 50 requirements are not confined to the prescriptive limits that apply to LWRs. Many other issues exist and have been propagated through the fifty-plus-year regulation history of the AEC and NRC. Regulations are dynamic, especially with a changing, complicated industry such as nuclear power. This is advantageous for technological progression and adaptation to the newest technologies. However, it also has drawbacks, especially when inconsistencies that result from this ever-changing regulation environment contradict themselves and cause confusion [10]. The inconsistencies that have arisen in the development of the Part 50 technical requirements are another issue that must be avoided in the development of Part 53 and the NRC's attempts to modernize the licensing process.

2.3.3 Lack of Consideration of Risk

Another problem in the development of the AEC's Regulations was the lack of influence of the concept of "risk" in their creation. This was due, in part, to a lack of experience with operating nuclear reactors at the time. Probabilistic Risk Assessment (PRA) Methodology, the NRC's current method of evaluating safety in reactor designs, was developed after the initial introduction of the technical requirements in Part 50. This lack of PRA being present at the genesis of the NPP technical requirements contributed to the prescriptive nature of the criteria. This is because PRA is a risk-evaluation method that allows for a technologically inclusive framework since it is not standardized to a specific design. Evaluating risk independently for each applicant helps in creating a risk-informed, performance-based regulatory process; if the *outcomes* of risk-analysis are tolerable and within margin, then the design is approved, and this approval can be granted independent of the technology that is utilized. This case-by-case evaluation has not been the approach for most of the AEC/NRC regulatory history.

2.3.4 Lack of Computing Capabilities

Lastly, relative to today, computing capabilities were limited at the beginning of the development of the NRC's regulatory framework. Analytical computer models were used by applicants to evaluate their reactor designs and demonstrate their safety in an application. With inherent low fidelity, the designers would assume large safety margins to mitigate risk based on the data of these models. Thus, high uncertainties were associated with these models, which meant that a conservative approach was taken by the NRC to ensure they had proper safety margins. This conservative approach based on the lack of computational insight compounded one another, which resulted in more restrictive measures than were necessary.

The crudeness of these models was due to a couple of circumstantial factors. The first, which has already been addressed, was the limited computing power. The fidelity of the models of the Cold War era pales in comparison to that of today, even though they were cutting-edge for their time. Second, there was limited experimental data to validate the models considering nuclear was a fairly new technology at the time. This was also a problem because many models were empirically based (based mostly on experimental data, not the underlying physics). Any computational engineer knows that a model is nothing but numbers if it cannot be validated with experimental data that accurately represents the phenomenological behavior that is being simulated. And even if there are data, repeated data are preferred. The combination of data gaps and lack of computing power both contributed to the need to provide safety margins that were much larger than required.

With regards to M&S, relatively limited computing capability is probably the most relevant issue with the old licensing process. It demonstrates how closely the ability to accurately model reactor processes and effectively regulate nuclear power are related. If uncertainty in analytical models is high, then regulations will not be as informed as they could be. Thus, the NRC and the industry must keep the improvement of M&S tools at the forefront of its licensing modernization efforts. However, how exactly to improve these tools is what is difficult, costly, and less straightforward.

2.4 Advanced Non-LWR Overview

Several advanced non-LWR designs have come to the forefront over the past decade. A nationwide desire to decarbonize the electricity grid, combined with a worldwide low-carbon energy shortage has catalyzed this return to innovation on the research and development (R&D) side of nuclear science and engineering that seems to have more traction than efforts to do so previously. However, overcoming the hurdles necessary to become licensed and implement these designs, of which there are many, has yet to be accomplished by any of the emerging non-LWR designs. An averseness to new technology from a utility, high costs associated with paying the NRC to review an application, and the expense of putting an application together are all obstacles that must be overcome by advanced reactor vendors [10]. Regardless, the technology is relatively familiar, and the R&D efforts have been increasing. There are still scientific challenges to be overcome, but a licensing framework that is not fit for non-LWRs only increases the difficulty.

For context regarding these new technologies and how they differ from traditional LWRs, each of these emerging reactor technologies and a brief explanation of their configurations are presented here. Figure 1 [12] represents the diversity of these designs. This diversity among non-LWRs is another reason why the licensing process must be reevaluated. A technology-inclusive framework is necessary to evaluate *all* different reactor designs. It does not need to be changed to fit another one or a few specific advanced reactor technologies, for this would only transplant the prescriptive issue to another reactor design.

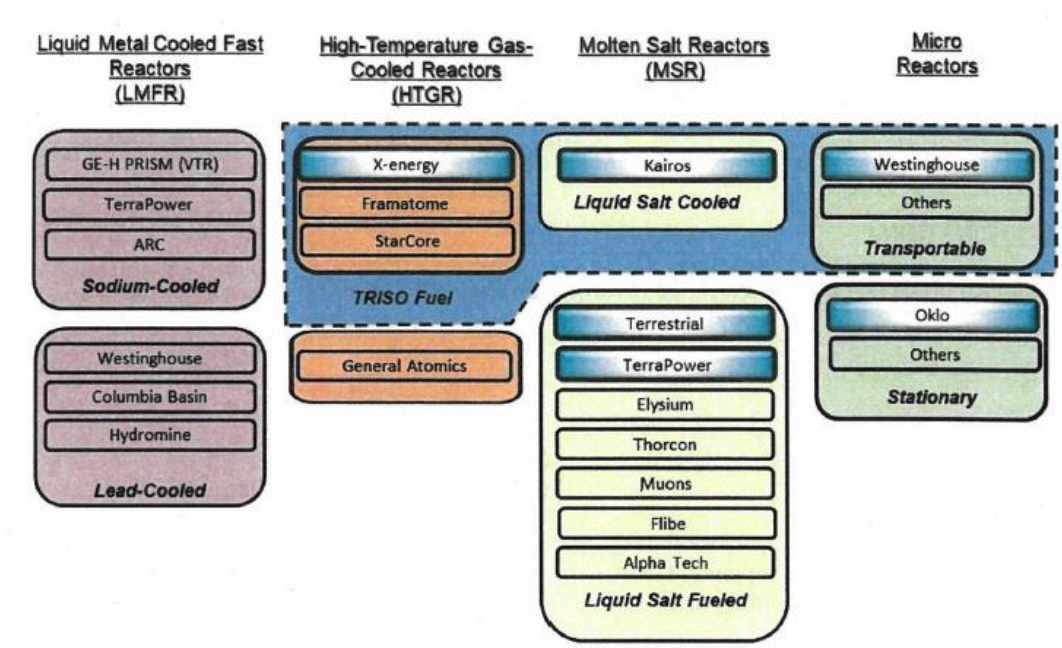

Figure 1. Companies developing advanced non-LWR reactor designs. [12]

2.4.1 Liquid Metal Cooled Fast Reactors

Advanced reactor designs can be divided into four broad categories, the first of which is Liquid Metal Cooled Fast Reactors (LMFRs). The potential advantage of LMFRs is that they use liquid metal, usually either sodium or lead, as a coolant, which allows for higher operating temperatures and lower pressures than water-cooled reactors of today [13]. This theoretically improves the safety and efficiency of the entire system. The term “fast reactor” also denotes that the fast neutron spectrum will be utilized, which means the neutrons do not have to be slowed down like they do in reactors of today.

2.4.2 High-Temperature Gas-Cooled Reactors

The second reactor design category is High-Temperature Gas-Cooled Reactors (HTGRs) or Very High-Temperature Reactors (VHTRs) and is primarily dedicated to electricity production but could also be used for hydrogen production [13]. A form of this technology has been proven in the United States at the Fort St. Vrain NPP (FSV) and the Peach Bottom Demonstration NPP. Current designs use helium as a coolant, which allows for extremely high operating temperatures. This higher temperature operation could enable extremely efficient electricity production [13]. Most of these reactor designs use Tri-structural Isotropic (TRISO) fuel. TRISO particle fuels are more robust than traditional nuclear fuels, which could improve fuel performance and safety. This enhanced safety can be attributed to the fact that it is highly unlikely the TRISO fuel will melt inside a reactor.

2.4.3 Molten Salt Reactors

Molten-Salt Reactors (MSRs) either use liquid fluoride or chloride salts (liquified from high temperature operating conditions) as a coolant, MSCRs, or as a fuel and a coolant, MSFRs. If the MSRs only utilize salt as a coolant, they can also use TRISO fuel. However, if fuel is directly dissolved in the salt, it is normally a liquified mixture of sodium, zirconium, and uranium fluorides [13]. Using molten salt as a coolant and/or fuel allows for operation near atmospheric pressure, which could be an added passive safety feature. Additionally, if the reactor is salt-fueled, then the fuel cycle is closed, which allows for other improved features like efficient burnup of plutonium and minor actinides [13]. This feature theoretically decreases the overall waste volume, which is another one of the many potential advantages compared to traditional LWRs that MSR developers boast.

2.4.4 Microreactors

Microreactor is a term used to describe very small reactors with electricity production ranging from 1 MWe to 20 MWe. These can either be transportable, like Westinghouse’s eVinci reactor, or stationary, like Oklo’s Aurora. These reactors have been designed to be simple, passively safe, reliable forms of energy for a variety of applications such as off-grid communities, emergency relief, and military applications. For example, the eVinci uses heat pipes to passively extract heat [14], which allows the reactor to remain in a pseudo “solid-state,” reducing the number of moving parts required. Microreactors do not have to be heat-pipe cooled; in fact, they usually utilize one of the three technologies presented above—just on a smaller scale.

Now that a brief overview of each reactor design has been presented, it can be observed that a regulatory framework that is prescribed for the LWRs of old is not suitable for these new, versatile designs. Also, this technological diversity displays why having adequate M&S tools fit for any technology is essential to efficient regulation. It shows that regulators will not be able to exclusively use technology-specific computer codes but instead will need to possess codes that can easily be adapted to handle a large variety of technologies. However, technologically specific codes will remain in use due to the complexity of differing advanced non-LWR technologies. This need for access to proper computer codes, whether they be technologically inclusive or specific, reinforces why the NRC must place a continued emphasis on the development of analytical M&S tools.

3. Current Status of M&S Involvement in Licensing Modernization

Over the past 50 years, many efforts have already been made by the NRC to modify the plant licensing process to be better suited for non-LWRs in some fashion. However, Part 53 is the first time an attempt to develop an entirely new licensing model has been promulgated. Officially developing Part 53 was prompted by NEIMA [3] when it was enacted in 2019, which directed the NRC to officially modernize the framework.

Outside of Part 53, other projects have been undertaken to improve the NRC's ability to license advanced reactors in the past decade. These projects were coordinated by either the NRC, a policy organization, or industry, or involved a collaboration between several different entities. These initiatives have laid out how the NRC plans to modernize but have also given insight into how the industry expects a modern regulatory framework to be conducted. Two of these projects that are especially relevant to the NRC's efforts in the area of modeling and simulation will be outlined here. Additionally, a general overview of the actions the NRC has taken thus far to ensure the adequacy of their M&S tools will be presented.

First, in December of 2016, the NRC published a document titled *NRC Vision and Strategy: Safely Achieving Effective and Efficient Non-Light Water Reactor Mission Readiness* (VS) [15]. This document was published by the NRC in response to an intra-agency realization that non-LWRs were a serious possibility, and that the NRC needed to be prepared to license them within the decade after the VS was published. The VS outlines how the NRC is going to ensure technical readiness, regulatory readiness, and how they are going to communicate with the public throughout. Here, the focus will be on how the NRC plans to ensure technical readiness, specifically, the development of analytical, or M&S tools. Second, in 2019, Southern Company and the Nuclear Energy Institute (NEI) collaborated to develop the Licensing Modernization Project [16] (LMP). The LMP developed a systematic method for identifying elements that are key to assessing plant safety in a technologically inclusive, risk-informed, performance-based manner.

3.1 NRC Vision and Strategy

The NRC Vision and Strategy document's main purpose was to effectively communicate the agency's plan to prepare to license advanced non-LWR reactors. It details how the NRC plans to "enhance technical readiness, optimize regulatory readiness, and optimize communication." This report will focus on how the NRC is improving its ability to technically evaluate the potential forthcoming fleet of advanced reactors.

The NRC presents several strategies they have developed to ensure technical readiness for the evaluation of advanced non-LWRs. Of these strategies, one explicitly addresses M&S, and its title is, "Acquire/develop sufficient computer codes and tools to perform non-LWR regulatory reviews." This strategy communicates the NRC's belief that M&S is integral to its ability to regulate advanced reactors effectively. To ensure its M&S tools are adequate, the NRC plans to leverage codes that have been developed by the NRC themselves, but they also plan to collaborate with the DOE, academia, industry, and international counterparts to develop these advanced modeling and simulation tools.

The main outcome since the VS document was released in late 2016 has been the utilization of the codes that have been developed by the Nuclear Energy Advanced Modeling and Simulation (NEAMS) Program. NEAMS is a DOE program that has been evolving since the early 2010s [17], but the NRC has incorporated these codes into a code suite that has been developed by the NRC themselves which is discussed in Section 3.3. The purpose of NEAMS is to develop a code that departs from the old empirical models, i.e., computer codes that rely mainly on experimental data, and instead create codes that rely more heavily on the underlying physics of reactors themselves. This approach requires much more computing power, but the recent advancements in high-performance computing (HPC) have made this approach a reality. And since these models will be composed mostly of multi-physics analysis capabilities instead of experimental data, their versatility in analyzing multiple different reactor configurations expands far beyond what the old LWR codes were capable of. However, this multi-physics, integrated code suite approach also increases the complexity of the models, which requires more familiarity, skill, and expertise [18]. How the NRC is preparing to develop this newly required expertise, how some has already been acquired, and the status of the NEAMS program will be addressed in Section 3.3 of this report.

3.2 Licensure Modernization Project

The LMP can be described as, "a project being led by Southern Company, coordinated by the Nuclear Energy Institute (NEI), cost-shared by the DOE with active participation by the U.S. NRC." [19] This integrated structure is what makes the LMP such a valuable project. There was involvement from every facet of nuclear power: Southern Company from industry, the NEI as policy organization and industry advocate, and the DOE and NRC, which represent the developmental and regulatory divisions of the federal government, respectively. The LMP's main objective was to collaboratively and holistically develop "technologically inclusive, risk-informed, and performance-based regulatory guidance" [16]. The core deliverable document of this project is the original guidance and recommendations to the NRC by the NEI [16], in a report designated NEI 18-04. The NRC then reviewed and ultimately endorsed this document in Regulatory Guide 1.233. [20]. NEI states that their purpose in conducting this project was to, "present a modern, TI-RIPB process for selection of Licensing Basis Events (LBEs); safety classification of structures, systems, and components (SSCs) and associated risk-informed special treatments; and determination of defense-in-depth (DID) adequacy for non-LWRs".

In the 95 pages of NEI 18-04, the NEI lays out a detailed guide to developing each of these parameters stated above. This guide is essential for non-LWR regulation, for it can be used to "develop logical, coherent, and complete bases for the development of the safety design; and, evaluation of the safety design based on the specific technology and design," [16] for advanced reactors. Before the development of this guidance, advanced reactor designers would have to conduct a series of meetings with the NRC to arrive at a consensus interpretation of the LWR design requirements that fit their non-LWR design. NEI 18-04 is extremely broad and covers a wide range of categories. For this paper, the guidelines the LMP provides that are pertinent to M&S will be presented here.

LBEs are events that encompass "off-normal" events like design accidents that result from events within the plant external accidents that are caused by events outside the plant (e.g., an earthquake or tsunami). The LMP process provides a systematic methodology for designers and applicants to use in determining if operations of a reactor are of sufficient risk to the *public* and *need* to be evaluated, i.e., if an accident is going to escalate in severity.

The systematic LBE identification methodology is relevant to M&S because all the information that is produced from this "Licensing Basis Development Process" (LBDP) is then imported into models to evaluate the safety of the reactor and perform confirmatory analysis, e.g., which components need to be simulated, which actions they perform that need to be simulated, etc. The LBDP narrows down how many activities need to be modeled, thus eliminating time lost to the simulation and evaluation of many extraneous events that are irrelevant to the *safety of the public and the environment*. The PRA obtains the probability of these accident sequences occurring. Then, the consequences of these accident scenarios are obtained by modeling the plant's behavior during the specific accident scenario of interest. Then, risk can be calculated by multiplying the probability of an accident scenario by the consequences of the accident. A visual representation of the development of an initial PRA model that represents this process is provided in Figure 2.

The PRA process exemplifies why being able to *accurately model advanced reactors* is crucial to determine their safety, and the development of NEI 18-04 reinforced this notion. The NRC's endorsement of NEI 18-04 as a regulatory guide is also reflective of the agency's belief that

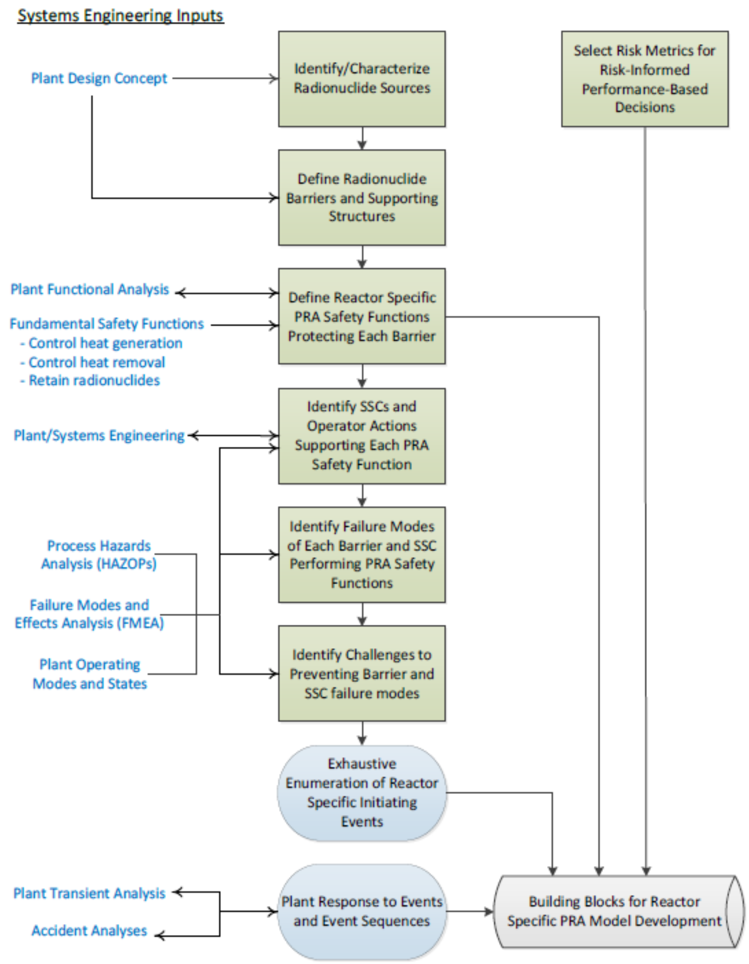

Figure 2. Example of an initial PRA model. [16]

M&S needs to be integral to the regulatory process. Before NEI 18-04, the guidance was to prescribe the events that needed to be simulated, which was not as effective when sufficient experience with the plant technology was not available, as is the case with advanced non-LWRs. However, this took large amounts of extra time [18], which can now hopefully be avoided with the systematic methodology NEI 18-04 provides for selecting LBEs.

3.3 Status of Modeling and Simulation Efforts

Along with the VS document and the LMP, it is necessary to give an update regarding where the NRC's efforts currently stand concerning how it is going to ensure it has access to adequate M&S tools to assist in licensing advanced reactors. Dr. Steve Bajorek, the lead on developing simulation tools for non-LWRs, published a paper titled "The U.S. Nuclear Regulatory Commission Approach to Modeling and Simulation of Advanced Non-LWRs; Preparing for the Next Nuclear Renaissance" [19], which thoroughly outlines the codes that will be utilized to analyze different reactor cycles. Additionally, Bajorek addresses how M&S will continue to be integrated into the review process.

Bajorek's paper mainly focuses on the Comprehensive Reactor Analysis Bundle (BlueCRAB or CRAB) code suite, which incorporates codes from the DOE NEAMS program, NRC codes, and commercial and international sources. While this integration into BlueCRAB is a new effort, some of the codes have been around for almost 40 years [21]. The goal of CRAB is to leverage the advancements in multiphysics simulations tools (i.e., analyzing areas like thermal-hydraulics, reactor kinetics, chemistry, etc. at the same time) that have come as a result of the progress that has been made in areas like high-performance computing in recent years. Thirteen codes comprise CRAB, each focusing on a different area of plant simulation. A schematical representation of this integration can be seen in Figure 3. Many different physical phenomena are involved in converting the energy released from a nuclear fission reaction into electricity.

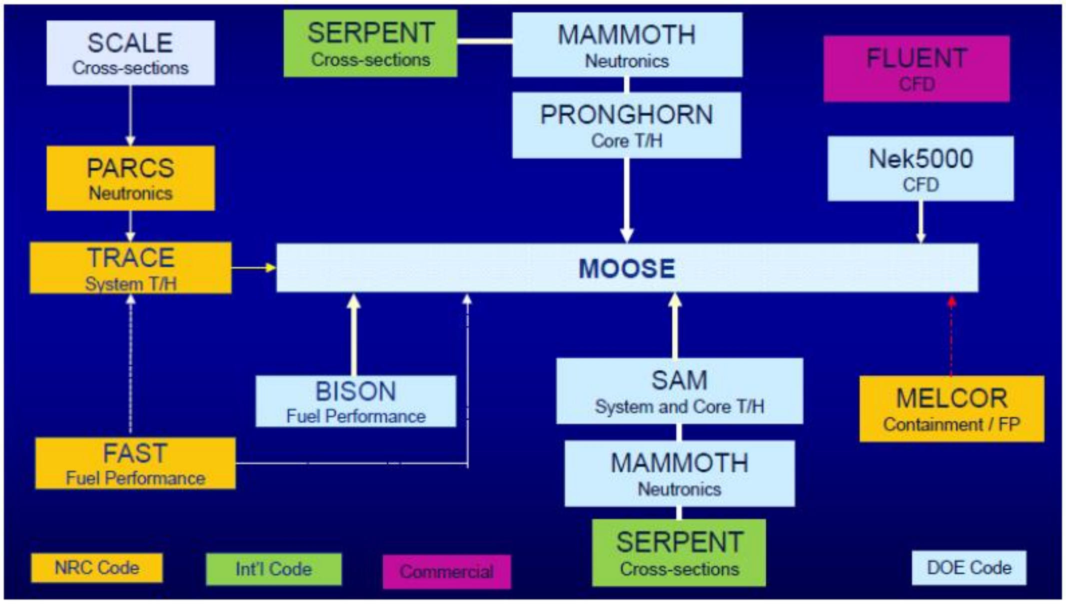

Figure 3. Schematical representation of the BlueCRAB code suite framework. [19]

Accordingly, CRAB not only has the capability of simulating a wide range of such phenomena but how these phenomena are specifically utilized in a reactor. Areas of nuclear engineering like thermal-hydraulics (TRACE, PRONGHORN, SAM), fuel performance (BISON, FAST), reactor kinetics (MAMMOTH, SEPRENT, PARCS, SCALE), accident progression (MELCOR), and more.

In a conversation with Bajorek in June of 2021 [18], he gave valuable insight into where the NRC's efforts in the M&S currently stand and how the NRC's focus has shifted in technically evaluating reactors. He confirmed that the main goal of the NRC has returned to identifying the maximum threat scenarios and what happens when these scenarios take place, as compared to a comprehensive reactor analysis. Dr. Bajorek claimed that while determining whether something will go wrong has an economic incentive for the vendor, that is not the NRC's concern. Now, the concern is identifying a couple to three "maximum hypothetical accidents," simulating said accidents, and characterizing the source term at the site boundary. M&S is essential to accomplishing this because experimentally acquiring such data is not only extremely time and fiscally intensive, but it is nearly impossible to do so regardless of the cost. The NRC also plans to increase coordination with the applicant to determine these maximum-threat events rather than diagnosing them independently. This decision to work more closely with the applicant will surely increase communication and efficiency in the licensing process.

However, Dr. Bajorek also said that with these new reactor designs comes an increase in the complexity of model development. With LWRs, the flow of water was on such a large scale and its flow parameters were so dominant that there were a lot of physical characteristics that could be neglected. In contrast, the new non-LWRs (and some advanced LWRs) employ safety systems that are governed by the natural laws of physics like gravity-controlled or naturally circulated fluids, rather than large pieces of turbomachinery to ensure coolant flow. This, "increases overall system simplicity, but it does the opposite to the complexity of the model." The physical laws that govern these safety systems are more complex to model than a large, powerful flow of water. Thus, many technical challenges still need to be overcome. But Bajorek asserts that these technological advances will be made because funding is available and capable individuals are being deployed to solve the technical challenges.

4. Analysis

Before the completion of this review on the NRC's plan to utilize M&S in the upcoming licensing of advanced reactors, I expected that the agency would be lethargic or slow-going avoidant with this issue since that is the stigma that independent regulatory agencies, or any government agency for that matter, carry with them when attempting to modernize or enact change. However, quite the opposite is true after investigating the agency's efforts over the past half-decade since the publication of the Vision and Strategy document and the enacting of NEIMA in 2019. The NRC seems to be doing everything in its power to ensure the development of proper analytical M&S tools to analyze advanced non-LWRs. A comprehensive analysis of the NRC's strategy and performance in this area based on the contents of Section 3 of this report will be presented below.

4.1 Strategy

In the VS document [15], which was written in 2016, the NRC outlines several strategies to ensure readiness for non-LWR licensing. The most relevant to this document is the "Development of Analytical Tools", which was then, not formally, but appropriately followed up by Dr. Bajorek's paper [19] about the NRC's approach to integrating advanced modeling and simulation into the licensing of advanced non-LWRs. The NRC has seemed to leverage its relationships with industry and the DOE rather thoroughly, as more than half the codes in the CRAB suite were developed by the DOE through their partnerships with universities and national labs.

As of January 2020, the NRC stated that the BlueCRAB framework and the codes that it contains are “out of the box ready to conduct significant verification and validation” of applicant’s designs [22]. More specifically, designs that will be submitted for review within the next half-decade. However, the NRC also admits that many improvements can be made to the BlueCRAB suite to increase fidelity. Bajorek ensures that these code development challenges are being thoroughly addressed by capable parties [18]. Additionally, the NRC has stated that there is a lack of experimental data available to validate codes that will be used to simulate advanced non-LWR operations. This is of particular concern since being able to validate models with experimental data is crucial to ensure their accuracy. This is an area that must be addressed soon by either the NRC, the DOE, or industry if the NRC wants to utilize the BlueCRAB suite to evaluate advanced reactors within the next decade. These concerns and recommendations for how to resolve them will be discussed in Section 5 of this report.

4.2 Performance

The NRC has also followed up on its intent to make policy changes and develop more applicable design requirements for non-LWRs. In addition to the VS, the LMP was another effort that assisted in developing a clear, systematic methodology for applicants to use to meet the NRC’s technical requirements. NEI 18-04 did an exceptional job at outlining proper techniques that applicants should employ to systematically identify LBEs in an RIPB manner. Overall, this effort was endorsed by the NRC and was established as a Regulatory Guide [20]. This was a progressive move on the NRC’s part, for it continues to shape the regulatory culture as “technology-inclusive”. It was another action promoting a change in the old ways and provided a PRA framework that can be applied to non-LWRs on an applicant-by-applicant basis. However, the true usefulness of the LMP will not and cannot be accurately determined until a vendor submits a license application.

Regarding code development, BlueCRAB efforts reflect an “all hands on deck” attitude put forth by the NRC with regards to ensuring adequate M&S tools will be available to handle reviewing advanced non-LWRs. The NRC seems to be taking the necessary actions to update its M&S framework to handle the anticipated wave of relatively unfamiliar non-LWRs. Time seems to be the only barrier at this point since gaining a solid understanding of each of these technologies is a task that, unsurprisingly, requires copious amounts of it. However, some areas need to be investigated that do not necessarily involve code development but are essential to validating and verifying the codes. And to regulate efficiently and effectively while remaining independent, these time-consuming tasks are necessary ones the NRC and the nuclear power industry as a whole need to prioritize, especially if they want advanced non-LWRs to be licensed as effectively as possible. There are also extensive validation needs for some of the codes in the BlueCRAB framework [22], which are addressed below.

5. Recommendations

Even though the NRC seems to be doing everything in its power at this point to ensure it has access to adequate M&S tools to evaluate advanced reactors, their preparation cannot be fully evaluated until Part 53 is finalized and these tools are employed. And although the purpose of this paper is to analyze the NRC's *current* policies towards incorporating M&S in regulating advanced non-LWRs, recommendations for how the NRC can continue its successes and address some already present concerns will be discussed below.

5.1 "Data Gaps"

Contrary to what some M&S experts preach in light of the advancements that have been made in multiphysics modeling, M&S evaluation methods are not yet a complete substitute for experimentation, at least in the eyes of the NRC [18] [23] [24]. Reliance on experimental data to validate models is still necessary, even though multiphysics modeling capabilities have increased in the recent past. Thus, in addition to code development that is already underway, there is still experimental research that needs to be done, i.e., experimentation to obtain data that can be used to validate M&S tools, that may be of equal or greater importance and concern.

The unbreakable rule of modeling and simulation is that models must be validated (V&V'd) by experimental data, or by comparison to another code that has been validated using experimental data. Regardless of the validation methodology, using experimental data to validate analytical models is necessary to confirm the fidelity of a computer code. This requirement is also reflected in 10 CFR 50.43(e), which requires an applicant have sufficient experimental information or operating experience to validate analytical models that evaluate the safety of a reactor design. There are specific reactor designs (MSFRs, MSCRs, heat-pipe reactors, LCRs) that lack experimental data or operating experience. However, all the codes used in the CRAB suite possess "data gaps" that must be addressed [22]. Ensuring the availability of funding to fill these data gaps is a concern that needs to be addressed soon to ensure that the fidelity of the models continues to increase and that the NRC's ability to effectively evaluate advanced reactors continues to improve.

5.2 Why Filling Data Gaps is Necessary

The US nuclear industry currently possesses thousands of years of LWR operating experience, as compared to mere decades of non-LWR operating experience [25]. As stated previously, there have been some non-LWR designs commercially operated. However, of the advanced non-LWR technologies having the potential for being submitted in a licensing application within the next decade, only the HTGR and SFR have previously operated commercially.

The relevant rule that requires analytical tools to be validated with experimentation is 10 CFR 50.43(e) [23], which states that when a reactor employs safety features that differ from those in LWR designs licensed before 1997, the applicant must demonstrate that the performance of each safety feature has been verified through analysis (M&S, usually), and if analytical tools are employed, then there must be sufficient data available for assessment of the tools. Even though this applies to the applicant, I believe the NRC must hold themselves to this standard as well if they plan to use their codes to evaluate designs. The alternative would be to rely on the codes of the applicants, but if the NRC wants to remain an "independent regulator," having its own reliable codes is the best strategy to ensure efficient and effective regulation[*].

For some reactor technologies, there are sufficient data to verify the analytical tools, particularly for HTGRs and SFRs. The NRC's exact wording was that the codes in the CRAB suite were, "… 'out of the box' ready to begin significant verification and validation, so that the [applicant's] code accuracy can be determined should an aggressive review schedule be necessary." [22] This is under the assumption that in [22], the NRC is referring to reactors such as the Natrium Reactor, an SFR being designed by TerraPower and GE Hitachi, and the Xe-100, an mHTGR being designed by X-energy. In this scenario, the BlueCRAB suite would be utilized by the NRC to evaluate an applicant's codes. If this is the approach the NRC plans to take when evaluating all licensing applications, then their codes need to be backed by sufficient experimental data if they are to ensure an accurate review of reactor designs and a proper evaluation of safety margins.

There are still "significant code development gaps" [22] in BlueCRAB's ability to model safety processes for *all* types of advanced reactors. The gaps are not significant enough to completely inhibit the NRC's ability to review reactor designs, but significant enough to limit the effectiveness and efficiency of the review. Thus, they are "good enough", but not finished. This is where the concern lies: that the NRC will settle for adequate instead of constantly improving the codes. A computer code is never "finished"; computer codes are always evolving and improving. And there are even larger gaps for specific designs, like MSFRs, that could keep them from being analyzed altogether [26]. This is not of primary concern since MSFRs are far from a developmental state that would warrant serious consideration for application submittal, but it still needs to be addressed if the NRC wants to be able to evaluate these designs whenever they do reach that point.

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[*] The NRC has not set forth a systematic way they are going to decide whether they will assess an applicant's codes with their own or by investigating the codes of said applicant. This is most likely due to their desire to keep advanced reactor licensing on an applicant-by-applicant basis.

Since the NRC's main objective is to regulate, it could be argued that this lack of experimental data is not their issue, and it should be assigned to the DOE to resolve. However, if the NRC plans to use the DOE's codes to evaluate the safety of reactors, then ensuring experimental data is generated to validate the BlueCRAB suite is crucial if they want to license as effectively as possible. Thus, these data gaps are of the NRC's concern as well.

5.3 Steps to Fill Data Gaps

When completing the BlueCRAB code suite, the NRC heavily leveraged relationships with academia, industry, the DOE, national labs, and international partners. This collaborative approach is the one they must take again when filling the experimental data gaps that the agency has identified in a series of reports [22] [27] [28]. Discussing the specific data gaps and the areas in which they lie is outside the scope of this report; therefore, this discussion will focus on how to ensure the gaps can be filled in a general sense.

Each of the five volumes of code development reports the NRC has published addresses one of the following specific areas:

1. Systems Analysis [22]
2. Fuels Analysis [27]
3. Severe Accident Analysis [28]
4. Dose Assessment
5. Nuclear Fuel Cycle Analysis

In the first volume, the NRC outlines significant data gaps and V&V needs for each code within the CRAB suite. For brevity, this will be the volume that is referenced here due to its broadness, for it deals with systems analysis, which is more all-encompassing and general than Volumes 2 and 3.

In Volume 1, the NRC gives an in-depth evaluation of the pros and cons of each code within the CRAB suite. Not all the codes are mentioned, but of the ones that are, six out of the eleven codes in Figure 3 still need verification and validation work in some capacity. However, the NRC does not lay out how this will be achieved—at least they do not in Volume 1. Thus, it is assumed that there is not a concrete funding plan to take care of these V&V needs. This is a challenging problem to tackle since conducting nuclear experiments and obtaining data is rather expensive. Therefore, as mentioned at the beginning of this section, the NRC needs to continue to prompt the DOE, academia, and industry to fund experiments that can obtain data that can meet BlueCRAB's experimental needs. The DOE and industry should be interested in conducting these experiments since they need the NRC to be able to evaluate their codes with BlueCRAB if they want their new reactor designs implemented.

5.3.1 DOE NEUP Funding

The NRC relies heavily on the DOE to allocate funding for activities like conducting nuclear experimentation [24]. The DOE facilitates several funding and grant programs, one of which is the Nuclear Energy University Program (NEUP). Universities are great at performing research, and the DOE's Office of Nuclear Energy (DOE-NE) has recognized this, as evident in their recent funding allocations. In June of 2020, the NE office awarded $55 million in grants to university-led projects via the NEUP [29]. These awards go towards projects focused on advancing nuclear energy with a focus on keeping America at the forefront of world nuclear innovation.

Within the NEUP, I suggest that the NRC encourage the NE office to give preference to research projects that want to assist in resolving BlueCRAB's validation needs. A specific emphasis could be placed on resolving these needs in the FY22 Request for Proposals, along with the years thereafter until the pertinent needs are met. If the goal of the NEUP is to keep America at the forefront of all NE advancements, then showing a preference for BlueCRAB experimental validation is an appropriate action. It is appropriate because all nuclear power must be regulated effectively if it is to be implemented effectively, and the NRC cannot do this without adequate analytical tools. This would also avoid having to increase federal funding and would take advantage of the programs that are currently in place.

5.3.2 Leveraging the NEET Program

One of the subprograms within the DOE-NE that could receive extra support to help resolve BlueCRAB's V&V needs is the Nuclear Energy Enabling Technologies (NEET) Program. NEET's mission is to, "develop crosscutting technologies that directly support and complement the Office of Nuclear Energy's development of new and advanced reactor concepts and fuel cycle technologies." [30] NEET is also closely related to NEAMS—NEAMS is under NEET's budget appropriation category in the FY22. The Gateway for Advanced Innovation in Nuclear (GAIN) Program, an initiative that provides U.S. industry with access to technological advancements in nuclear science through vouchers, is also coordinated by the NEET Program.

The V&V needs that are present within the BlueCRAB framework, which includes several NEAMS codes, are a prime example of an area of research that needs to be done that "crosscuts" multiple nuclear technologies. For example, TRACE is a thermal-hydraulics simulation code and is one of the codes that currently requires, "extensive code development and validation for non-LWRs." If NEET were to support an experimental program that helped fund experiments, whether conducted by industry, national labs, or universities, then this would not only provide the NRC with vital data to validate several different codes within the BlueCRAB framework, but it would also benefit all emerging advanced reactor technologies that are intending to submit a licensing application.

If advanced reactor technologies are going to be implemented efficiently enough to deliver on the benefits they have been claiming they can provide, then they must be licensed efficiently. The nuclear power industry is only as advanced as its regulatory body. Thus, obtaining the necessary data to validate the analytical codes that will be used by the NRC to regulate advanced non-LWRs is a task that NEET must seriously consider making a main priority. If the goal of NEET is to, "directly support and complement the NE development of new and advanced reactor concepts," then helping fund these experiments is an obvious choice for the DOE to make.

However, the implementation of this recommendation is not completely straightforward. Several options could be chosen to procure this experimental data. Industry, national laboratories, and universities were the parties mentioned here that NEET could fund to conduct the experiments. First, through the GAIN initiative, the DOE could give preference to applications that want to conduct experiments that would provide vital data for the validation of BlueCRAB codes. Usually, these experiments under a GAIN voucher are coordinated through a partnership between the company that received the voucher and a national laboratory. These vouchers are a vital piece of funding that should be leveraged by the DOE to support the development of the ability for the NRC to effectively regulate advanced non-LWRs.

If it is not through an industry-national laboratory collaboration, then NEET could fund experiments at universities with the capability to perform separate or integral effects testing. MSRs are the technology of consensus opinion that have the most data needs. Thus, a university like the University of Wisconsin-Madison, which can test molten salts in a variety of ways using their different salt loops [31], represents a potential relationship with academia that NEET should heavily pursue to perform these tests. Considering that there are relatively few universities with this capability, funding university-led experiments at national laboratories is another option that could be pursued.

6. Conclusions

Overall, the NRC has taken the necessary steps so far to update its M&S capabilities to be able to effectively evaluate and regulate the potential oncoming fleet of advanced non-LWRs. Also, the NRC has effectively communicated through two documents, the Vision and Strategy Document released in 2016 and Regulatory Guide 1.233, endorsing NEI 18-04, that they plan to keep M&S central to their licensing processes as they modernize their regulatory framework to be a better fit for non-LWRs. This decision to keep M&S integral to the regulatory process will ensure an effective and efficient evaluation of reactor designs, which will, in turn, pave a wider, more inclusive path for innovation in the nuclear power industry.

However, as the NRC has updated its M&S capabilities, they have also identified some concerns regarding the lack of available experimental data to validate some of the codes in the BlueCRAB suite. These experimental data gaps are not to be ignored, for if the CRAB suite is not continually updated and validated, proper margins will not be set. Thus, it is pertinent that the NRC leverage relationships with the DOE, academia, and industry to obtain necessary experimental data for advanced non-LWR modeling and simulation tools.

Acquiring this data is also essential to deploying advanced nuclear power as a solution to the low-carbon energy supply issues the United States faces as it tries to reduce its carbon footprint while retaining adequate power production capabilities. If the NRC decides to address these significant data gaps, which they should if they want to evaluate reactors as accurately and safely as possible, then enacting the policies provided in this report will surely assist the agency in acquiring such experimental data.

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