Design Readiness And Maturity Assessment (DRAMA) tool for Advanced Reactors[1]

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Abstract – *This research is developing a formal, repeatable method to assess the readiness and maturity of an advanced nuclear reactor design for licensing and deployment. This design readiness and maturity assessment (DRAMA) tool will be capable of determining the readiness of a design and of all parties needed to bring a particular advanced reactor design to fruition. Beneficiaries and stakeholders include the design team, research organizations (required to collect needed data and develop design tools), standards organizations, research facilities to support gathering of needed data, supply chain and construction organizations, and those responsible for legal and regulatory infrastructure (including defining import-export requirements). Recent experience has shown that even the most experienced engineering, procurement, and construction (EPC) organizations, with decades of experience in the nuclear power business, have had significant challenges in bringing designs to completion, licensing the designs, and constructing new plants. For new entries into the field, simply understanding the unique environmental, design, EPC, and operating requirements is daunting. A significant part of the challenge is that new entries into the market do not know what they don't know. The DRAMA tool will provide applicants with a better understanding of their design readiness to proceed to licensing (and steps in the process), while at the same time providing a valuable metric for other interested stakeholders, such as funding agencies, national regulators, and international markets. The DRAMA tool will provide an assessment of the likelihood of successfully completing licensing, EPC, and deployment. It will provide an assessment of the ability of the regulatory infrastructure and the supply chain to support the deployment of any design or class of designs. It will also help prioritize research and policy efforts to improve the likelihood of deployment of the next generation of advanced reactors.*

I. BACKGROUND

Many, if not most, of the advanced reactor companies that are developing new concepts for fission and fusion reactors have little to no experience in bringing designs to completion, navigating the engineering, procurement, and construction (EPC) process, developing the extensive supply chain needed to effectively construct reactors, and knowledge of the regulatory requirements for licensing a new reactor for construction in the United States (US) or elsewhere. Even organizations with decades of experience, like Westinghouse, have run into first-of-a-kind design, licensing, and construction issues that have significantly affected the readiness, licensing and construction timelines, and cost. Westinghouse's need to redesign the AP1000 shield building provides an example of how time and resources were significantly affected because the available American Concrete Institute (ACI) design code was not used, even though it was the endorsed standard by the U.S. Nuclear Regulatory Commission (NRC). Had a design decision been made sooner to either use the endorsed standard, or to proactively engage the NRC been made

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sooner, or had an updated ACI design code been available, significant additional work by the vendor and review delays by the NRC[1] could have been avoided. Another example is the review by the Finnish regulator, Radiation and Nuclear Safety Authority (STUK), of the instrumentation and control system design for the EPR. This system's inadequate design readiness caused years of delay at the regulator and significant delays and cost for the vendor.

The U.S. Department of Energy (DOE) and commercial vendors are supporting the Advanced Reactor Demonstration Program and the Risk Reduction for Future Demonstration projects. These projects are designed to accelerate the timeline to deploy advanced nuclear reactors domestically and globally. In many cases, this funding will be used to address some significant potential risks associated with the future deployment of these new reactor concepts, including new fuels, such as TRi-structural ISOtropic particle (TRISO) fuel, innovative cooling technology, such as passive heat transport systems, and challenges associated with modular construction and transportation of reactor modules. However, to move these designs from a conceptual stage to detailed design, and preparation for licensing, all the potential risks will need to be fully evaluated and design decisions made to support commercial construction of these reactors. This is also true of the other new concepts, including fusion reactors now in various design stages.

A number of studies have looked at how new reactors can play a role in the future clean energy needs of the world and the challenges that need to be overcome to ensure that nuclear energy plays its rightful role in the future. A recent MIT study, "The Future of Nuclear Energy in a Carbon-Constrained World"[2], is particularly appropriate to this work. The study found that having a complete design before construction began and the development of a proven supply chain were key indicators for increasing the probability of success in the delivery of new nuclear power plants. Other critical attributes for success include a flexible regulatory structure and emphasis on designs that can be effectively fabricated and constructed.

As a result of lessons learned from the new reactor reviews of the past, the NRC in the late 2010s added a "pre-applications readiness assessment" to its process of supporting vendors' development of licensing applications[3]. Although this process is now being used as part of the overall pre-application process for some potential applicants, it is too narrow in its focus and too late to support design decisions by the advanced reactor vendors. The assessment scope can include a review of the overall application but typically has been limited to selected parts of the application, such as those topics identified as challenging areas in prior application reviews (e.g., instrumentation and controls, seismic analysis, long-term cooling, and human factors engineering). This assessment focuses on the availability of appropriate documentation to support the application and, to a lesser extent, the availability of subject matter experts and is only valuable for supporting a vendor's assessment of the completeness of their application to be accepted for review by the NRC. Although this readiness assessment has limited use, it does demonstrate the significant need for readiness and design maturity. Additionally, other technology assessment to determine the readiness of current and future advance reactor designs have been suggested[4], but these assessments are not formal or repeatable.

Although the NRC effort has provided some insights to vendors, it will not help vendors understand how the lack of available information will impact their ability to be successful. To move forward, vendors must have data to support detailed design (including design data, or data needed to validate analysis and safety codes), validated design tools, a supply chain to support the construction of the design and must know the effects new technology and new design concepts have on the ability of the regulator to assess unique safety concepts or develop a new policy to permit these concepts to be accepted for use.

To show viability and proof of concept, this research will first develop a framework of key attributes for design readiness and maturity, drawing on both system engineering design readiness concepts and known information needed to support detailed design completion and licensing. The framework will establish the general information necessary, the level of completeness necessary for the information, and the relationships between design information and the ability of current infrastructure to supply information to support completing the design. The framework will also include linkage between advanced design concepts (inherently safe technology, remote operation, advanced fuels, etc.) and needed regulatory changes associated with them. This information is required to use the tool to assess the potential impacts of new technologies on licensing and deployment readiness for new designs.

II. RESEARCH APPROACH

As discussed above, this research will first develop a framework that integrates the attributes that most affect the design and infrastructure readiness, and maturity of the design and necessary infrastructure. The level of readiness will be an aggregation of design completeness (how much information is available), the uncertainty in the design information (validated design and safety analysis tools, supporting data, etc.), and the regulator's ability to come to a regulatory decision. The level of maturity (how final the information is) will be an aggregation of how sure the vendor is that the design is final, including the stage in the design process (conceptual design, preliminary design, testing, and demonstration, final design, etc.) and how sure they are that the design can be deployed (including supply chain readiness, export considerations, labor availability, site considerations, transportation, safeguards, fuel cycle considerations, etc.). The research will develop the attributes and the first and second-level interactions between the attributes into a basic framework. This will require both an effort to collect and analyze the information and validate the information's completeness. The research will use several information collection processes, including reviewing available technical and policy literature, interviews with vendors and regulators, and evaluating past efforts. The research will also use system engineering design readiness concepts to help develop relationships between readiness and maturity attributes. This will include metrics such as percentage of subsystems and system design reviews completed, planned corrective actions to address hardware/software deficiencies, adequate development testing, an assessment of development risks, conducted hazard analysis, identification of crucial system characteristics and critical manufacturing processes, and estimation of system reliability base on demonstrated reliability rates. By including well-known system engineering metrics, the framework will be better able to use notable interactions to structure the subsequent model.

The next major tasks will be to use the framework (see Figure 1) to develop specific readiness and maturity metrics and a model that will use qualitative and quantitative information associated with the attributes and their relationships forged in the framework. Additionally, overarching (site related) features will be added at this stage. The model will include information such as what regulatory system will be used to assess a particular design. Also, at this point, various generic information and infrastructure information will be added. This will include industry standards, availability of regulatory policy to support unique design attributes, and chosen licensing framework. The typical time needs of a particular design process and regulatory framework (including uncertainties) will also need to be included at this stage.

The modeling methodology that will be used to construct the model will be a multi-attribute utility function. This methodology has the advantage of being able to use utility functions to effectively represent both qualitative and quantitative attributes and explicitly include uncertainty in the modeling of each attribute. The project will also investigate other potential methods such as AI and machine learning to determine if these methods would improve the tool's effectiveness.

The next stage of the work will structure the method for specific uses, including providing input to the advance reactor vendor decision making regarding areas of the design to work on with priority, inputs to organizations conducting research to support advance reactor development (such as DOE), inputs to funding organizations (to support the down selection of potential conceptual design for funding), inputs to regulatory agencies to support infrastructure development or other purposes. At this stage, the DRAMA tool output will need to be effectively designed to provide a readiness and maturity scorecard that will show the design's readiness to move to detail design and to licensing in easy-to-understand terms. The scorecard will include a licensing readiness metric, a cost metric, and an infrastructure metric.

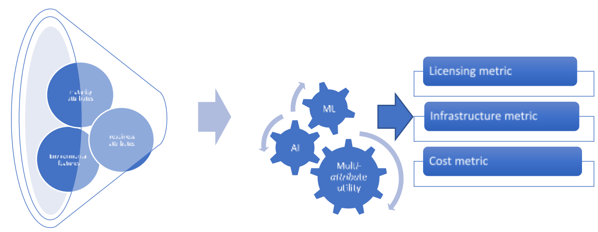

Fig. 1. DRAMA tool high level structure

The project's final stage will be to test the DRAMA tool using several designs to ensure its usability and effectiveness. This will be done using two or three designs that are in the current licensing process. When complete, the DRAMA tool will be updated using the lessons learned from the process and tool testing. This work will provide a level of assurance that the tool is useable and reliable. Although not a formal verification and validation of the tool, it will provide confidence in the quality of its output.

When complete, the DRAMA tool will be sufficiently flexible to support vendors that will be required to have their designs reviewed using different regulatory requirements associated with diverse regulators in the U.S., such as the Department of Defense for microreactors, DOE for test reactors such as the Versatile Test Reactor and NASA, and other countries that have formal reactor regulations. It should also be helpful to regulators, that are in the process of developing new regulatory requirements and infrastructure, such as the NRC's ongoing effort to develop regulatory infrastructure for fusion reactors.

III. ASSESSMENT STRUCTURE

It has been determined that the best input structure for the assessment tool would be a simple set of development attributes assigned to eight attribute classes. These will be Design Completeness; Design Uncertainty; Regulatory Readiness; Design Maturity; Design Deployment Risk; Regulatory Structure; Political Environment; and Supplier, Operator and Regulator Relationship. These attribute classes were chosen to both maximize the capability to develop the data to support the assessment and to help provide a link between the issue's designs are facing, such as design completeness and regulatory readiness and the outputs of DRAMA. It should also be pointed out that in the ideal case we should try to ensure that all the attribute classes and the individual attributes are independent of each other and to the greatest extent possible orthogonal, the reality is this can't be practically achieved. There are so many subtle dependencies between the attribute classes and the individual attributes that any effort to make these independent will only cause the input space to be both confusing and difficult to use.

Within each attribute class there will be a number of individual attributes. For example, within the Regulatory Readiness attribute class, individual attributes will reflect the ability of the regulator to come to a regulatory decision. The attributes in this class will depend to some extent on what regulatory decision is being sought. For example, in the US, the NRC could issue a design certification or a combined operating license, using the part 52 process or a different set of approvals using the part 50 process. For the initial development of the DRAMA tool we will use the part 52 design certification and early site permit as the base regulatory decision and deal with the other design decisions possible as part of the Regulatory Readiness attribute class. The Regulatory Readiness attribute class will also include possible different countries regulatory structures as well as different use cases (for example research reactors or reactors license for use by government facilities). The attributes for the Regulatory Readiness class include the need for a case-by-case determination of the size of the emergency planning zone, the ability to meet the standard principal design criteria without requesting revisions, the availability of regulatory analysis tools, the ability of the regulator to apply the current regulations to the technology being proposed, the availability of codes and standards, and the availability of regulatory staff to complete the review in a timely manner. Some of these attributes can be quantified, such as the percentage of requirements that can be met without requesting exemptions, but many will need to be qualitative. This does not present a challenge, so long as the qualitative value is consistently assessed for different technologies. As can be seen from the above attributes there will be dependencies on these attributes with attributes from the Design Completeness and Design Maturity attribute classes. These dependencies will be addressed as part of the utility function structure so that the assessment of individual attributes can be done in a straightforward manner.

As discussed above, individual attributes can be either qualitative or quantitative and will be converted into a specific utility for use in the multi-attribute utility function for each of the output metrics. The particular type of utility function analysis that will be used is Structured Value Analysis that is frequently used when dealing with the evaluation of imprecise and intangible values[5]. The Structured Value Analysis approach is especially useful when the decision maker must consider multiple diverse acceptance criteria. In this approach, each parameter is assessed based on a value function (a class of utility functions) and a normalized weight based upon the importance of the parameter. An aggregate of the overall value of all factors is then calculated and is used as an index for decision making. Consider the case in which an evaluation of the capability of particular options based on acceptance criteria characterized by parameters i (such as cost or risk). Further, assume that the value functions, associated with each parameter i, are u_i. For this effort the utility value u_i is the effect any particular attribute has on the likelihood of success with respect to the given output function (Licensing, Infrastructure or Cost). For example, the attribute associated with the ability of the design to meet standard principal design criteria without the need for exemptions would have a value function ($u_{3,6,3}$) with respect to the cost outcome. Value functions are assigned values by the decision makers depending on some predetermined metric and/or their preferences and beliefs and are frequently weighted to assign an importance W_i. This weight is a subjective value expressed by the decision maker directly or through generation of data based on past experience. Then the linear aggregated weights of all parameters would be:

$$V = \sum_{i} u_i W_i$$

Other more complicated forms of this equation can be developed to account for the dependency that exists between the attributes value function (u_i). The weights as well as the value functions will be assigned base on information gained through review of past and current experience and interviews with key stakeholders. This is an area where AI may be used when the structure for the model is complete and information gathering is sufficient to support training a model.

Each output value V is then a function of all of the attributes and their weights. This method also allows for consideration of uncertainties in both u_i and W_i values, by propagating these uncertainties to express the values of V in terms of probability distributions. For the purpose of developing the dependent relationship the mean value will be acceptable. But this will be expanded to include the distributions depending on the need for sensitivity studies to develop a better understanding of the data. As discussed above the output will include a licensing readiness metric, a cost metric, and an infrastructure metric. These will be normalized to a given base case (for example, the ability to meet a given licensing timeline). By doing this, a more aggressive metric can be analyzed (for example, a shorter licensing timeline, or one with lower cost) by simply modifying the attributes value functions u_i.

IV. STATUS OF RESEARCH

Although this research begam only recently, it is based on a number of reviews of the issues associated with both nuclear specific and general large scale construction projects have experienced[2,6]. The research will also use system engineering tools and experience to develop the utility functions for the analysis and will develop these into the formal structure outlined earlier. The basic structure is expected to be complete by the fall of 2021, with the tool ready for testing and benchmarking by the spring of 2022.

IV. SUMMARY

The goal of this research is to develop a formal, repeatable method to assess the readiness and maturity of advanced reactor designs to be license and deployed. The DRAMA tool will provide an assessment of the likelihood of successfully completing licensing and deployment and will also create the capability to assess the ability of regulatory infrastructure and the supply chain to support the deployment of any design or class of designs. It will also help prioritize research and policy efforts to improve the likelihood of deployment of the next generation of advanced reactors.

The DRAMA tool will use multi-attribute utility methods to support qualitative and quantitative estimates of readiness and maturity and uncertainty estimations to effectively support assessment of the likelihood that new designs will be successful. DRAMA will also support informed decisions by vendors, regulators, and researchers on where to provide resources from a strategic standpoint to make the most significant impact on the advancement of both individual designs and on the advance reactor sector. The DRAMA tool will address challenges at the overall design level, the system design and subsystems design level, and the conceptual level. Additionally, design readiness and maturity can also be affected by the vendors' design philosophy and encouraged by funding organizations, like the DOE. A design that uses established concepts and well-analyzed phenomena will be easier to design and license than relying on new ideas that may not have the analysis, data, and operational experience as more conservative designs. The more aggressive the use of innovative but untested concepts and systems, the more challenging the analysis, licensing, and deployment. The DRAMA tool should be used to support studies to evaluate the risk of use of new innovative concepts and methods will have on the likelihood of success of any particular project and its cost and schedule.

The DRAMA tool could also be used to assess the potential impacts of new technologies on licensing and deployment readiness for contemporary designs, as well as how challenging it will be for new technologies to be integrated into needed reactor operational programs, including the development of adequate technical specifications, maintenance, and back-end fuel cycle tasks.

REFERENCES

1. ANS Special Committee on Advance Reactor Policy, *Special Report, Setting the Right Bar: How Consensus Standards Help Advanced Reactor Development*, American Nuclear Society, LaGrange Park, IL, USA (2019).

2. J. Buongiorno, J. Parsons, M. Corradini, and D. Petti, *The Future of Nuclear Energy in a Carbon-Constrained World—An Interdisciplinary MIT Study,* MIT Energy Initiative, Massachusetts Institute of Technology, Cambridge, MA, USA (2018).

3. U.S. Nuclear Regulatory Commission, *Pre-application Reediness Assessment,* NRO-REG-104*," (ML14079A197)*, Washington, D.C. (2014).

4. *Nuclear Reactor Technology Assessment for Near Term Development, IAEA NE Series NP-T-1.10*, International Atomic Energy Agency, Vienna (2013).

5. W.D. Rowe, *An Anatomy of Risk,* John Wiley & Sons, New York, (1977).

6. CRUX, *Engineering and Construction, A Regional Analysis of Causation: Lessons Learned from Claims and Disputes,* (2020).