Essential Elements of a Nuclear Construction Feasibility Assessment

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INTRODUCTION AND MOTIVATION

No investment is without risk, but nuclear power plants have proven to be exceptionally risky economic and financial propositions for utilities in the United States. Historically, no commercial nuclear reactor construction project in the US was ever completed on budget, and nearly all were completed substantially behind schedule [1], leading to less-favorable economic prospects and high financial burdens for firms undertaking these projects. Extant work on this topic has explored high-level trends in cost escalation, but drawing specific conclusions about how to reduce risk through design or management practices is difficult in the absence of detailed data.

As of March 2018, dozens of reactor developer firms are working on innovative advanced reactor designs that incorporate robust new materials and elegantly engineered passive safety systems. Utilities' requirements for a reactor, however, are all measured against the yardstick of cost and financial risk. Interpreting actual cost or risk reductions achieved by design claims may be difficult, or require large uncertainty margins, in the absence of historical data with which to compare. For example, a design that uses 20% less concrete may achieve a concrete cost reduction of about 20%, but second-order feedback loops such as labor cost, schedule risk, formwork requirements, and ultimately capital-markets risk perceptions that will also alter the overall effect. A potential investor must be able to make a confident assessment of the economic prospects of a new reactor type. For this to be possible, the full scope of financial ramifications of every conceptual and technological design claim must be completely quantified.

In the context of the significant cost escalation encountered at the V.C. Summer and Vogtle expansion projects, and given the current uncertainties about SCANA's financial prospects and pending sale, it would be difficult to overstate the need to quantitatively identify and quantify the risks associated with building new nuclear power plants in order to eliminate or reduce them wherever possible. The ongoing dialogue between utilities and developers could be strengthened and facilitated across all advanced reactor designs by such a quantitative understanding.

Future nuclear power plants may differ significantly from conventional LWRs in design and scale. However, the best possible model of unexpected difficulties, cost escalation, and schedule slippage is still likely to be based significantly on the historical industry experience with nuclear construction. The technological and regulatory characteristics of nuclear projects are unique and cannot be simulated with other data.

To comprehensively address this need, a collaborative effort among industry and academia is needed. Original construction documentation and data must be located and digitized, and used to conduct a rigorous statistical post-mortem of nuclear project disruptions. The ultimate output of this analysis would be a **statistical risk register (SRR)**: a document enumerating all significant types of adverse events, probability distributions of their occurrence based on project parameters, and likely financial impact ranges. The SRR would provide information to utilities, capital backers, and developers about the practicable deployability of different technologies based on their technical characteristics.

Conversations in the industry indicate that US utilities are generally not interested in nuclear projects during the next decade. During this grace period, the development of this historical database and quantitative risk-analysis capability can smooth the way for eventual serious discussions of advanced-reactor deployment in the United States.

Attempts to design reactors that are actually constructable and likely to exhibit favorable financial performance must be predicated upon detailed understanding of actual sources of cost-estimation mistakes and project-execution risk. Utilities that may consider these projects, and private capital that might back developers, should also be given the opportunity to learn from the experiences of all of their peers, rather than their own limited project set.

DEFINITIONS

In the context of this paper, an **adverse event** or **project disruption** will refer to specific instances of project cost escalation or schedule slippage, or the causes thereof.

Project parameters will refer to metadata about the project that is likely to influence its course, such as reactor design/type, location, financial statistics of the parent utility, local market structure, and other important details.

A **risk chokepoint** will refer to any potential adverse event with both a high likelihood of occurring and a large associated likely cost increase or delay. Risk chokepoints may be items of focus for future risk-reducing design or additional management oversight.

RISK AND REWARD IN CAPITAL INVESTMENTS

The importance of a low levelized cost of electricity (LCOE), and of managing total plant costs, is well understood in both academic and industry circles. However, LCOE and total cost are insufficient to fully inform the actual utility decision-making process when considering major investments in capital assets. These factors also do not sufficiently characterize private capital's approach to evaluating potential projects for backing. Equally important is a thorough, quantitative understanding of the risks involved in the execution of such a project, and subsequent operation of the plant. These risks include **economic risks**, which are related to the total cost outcome of a particular project, and **financial risks**, which represent trickle-through effects of project economic issues on the overall financial performance of the company.

Economic risks—those of cost overruns and schedule slippage—have a substantial impact on the overall acceptability of a potential nuclear construction project. Estimating the likelihood of adverse outcomes in construction and the range of potential consequences requires detailed data encompassing a wide range of historical projects, and cannot reliably be accomplished by examining records of overall total cost outcomes. In particular, constructing probability distributions and identifying the highest-priority (high-probability, high-consequence) project disruptions is nearly impossible using currently-available data.

In addition to economic risk, financial risk is a material consideration in the decision to build a nuclear power plant. For an investment of this size (namely, similar in scale to a utility's total financial resources), economic risks translate into direct and indirect financial risks to the utility that can diminish the feasibility of a proposed project, due to potential threats to the firm's overall financial health. Direct financial risks include uncertain impacts to the balance sheet, the accumulation of unexpected additional debt, and the issuance of unexpected additional equity to finance the project. Indirect financial risks comprise the potential for debt overhang/crowding out of other capital investment plans, as well as the negative impacts of increased perception of risk in the utility's operations: potential credit downgrades, increased hostility from ratepayers, and additional regulatory scrutiny of rate cases.

The development of the statistical risk register would support quantification and management of both risk types. Because financial risks flow through from the underlying construction-cost risks, properly estimating them requires a quantitative understanding of the likelihood and magnitude of potential adverse construction outcomes. This information would be invaluable in determining the financial-risk characteristics of advanced reactor designs currently in development and identifying which are the most economically feasible. Development of the statistical risk register would allow utilities to rigorously evaluate potential advanced-reactor projects according to directly-relevant financial criteria, and provide important feedback to developers on the acceptability of their designs.

These same considerations also flow through to the venture-capital decisionmaking process; the viability of each reactor as a product and investment ultimately depends on its economic and financial appeal to utilities.

PREVIOUS EFFORTS

The concept of studying costs and cost increases for nuclear reactor construction projects is, of course, not new. Since the early days of nuclear power in the United States, cost has been a pressing concern for utilities considering investing in plants. However, past studies have generally been limited to regression-style, high-level examinations of general trends, due to the lack of detailed data available for analysis. These limitations make it difficult to derive specific insights about constructable design and efficient management practices that might optimize the economic prospects of future nuclear plants.

Contemporary sources, such as Bupp and Derian's 1978 book "Light Water" [2], and the seminal 1986 EIA report "An Analysis of Nuclear Power Plant Construction Costs" [1], offer insights into developing concerns about cost increases during the heyday of nuclear construction in the US. However, they lack complete historical perspective, as they were limited to discussion of projects completed or ongoing at their time of writing.

Post-boom (1996 and onward) sources have the benefit of additional historical perspective, and in some cases extensive comparison with international experience, but are also limited to regression analyses of total project costs and investigation of general variables such as location and plant type. Koomey and Hultman [4], Grubler [3], and Lovering et al. [5] offer thoroughly-researched recent perspectives on the full sweep of US experience with reactor construction.

REQUISITE DOCUMENTATION

Many types of quantitative and qualitative documentation and data would support an analysis of this kind. Any records that can be located could likely be incorporated into some kind of analysis. In particular, the following document types should be prioritized:

- Contracts for EPC services, labor, and major equipment/materials items
- Any amendments to the above contracts
- Change requests and change orders, especially including timestamps, dollar amounts, and reasons for changes
- Project estimates from all stages, especially including backup documentation
- Expense-tracking documentation, especially as correlated to the overall code of accounts
- Retained copies of EIA-254 and ERDA-254 filings (mandatory semiannual reports filed by utilities during the construction of each reactor unit, including expenditures-to-date for major line items, updated total final cost and schedule estimates, and updated estimates for milestone completion dates)

Documentation from the US nuclear power industry would be of the greatest importance. However, there are doubtless many parallels and lessons to be learned from nuclear construction experiences in other countries, and detailed datasets from international projects would make a welcome addition to the data described above.

POTENTIAL PROGRAM STRUCTURE

The goal of an endeavor of this kind would be to generate a statistical risk register for nuclear construction projects, backed by statistical and qualitative analysis of detailed historical project records. The register would indicate probability distributions for various classes and subclasses of high-consequence adverse events, and include commentary on their downstream effects on costs and schedules. It would also identify potential risk chokepoints where additional risk-reducing design work could significantly improve prospects for economic viability. Two types of activities would support the development of this document: data retrieval and database construction, and data analysis and reporting.

The Risk Register

A **risk register** is a project planning document that helps management predict and track potential sources of risk in the execution of a construction project. The register usually has three principal components:

- *Risk items:* Potential adverse events or circumstances that may cause cost increases or delays.
- *Likelihood estimates:* Rough probability estimates for each item, frequently scored on a "low-medium-high" scale.
- *Impact estimates:* Rough estimates of the likely cost or schedule impacts if the associated item were to occur.

For example, a risk register entry might read:

Item	Likelihood	Impact
Discovery of shallow sand beds not identified in site survey	Low	Moderate

These three components together can help generate a priority matrix, indicating which items rank highly in both likelihood and impact. These high-risk items can then be brought under more active management, or have additional contingencies included during the estimation and contract negotiation processes. The register can also contain information about planned risk mitigation strategies.

The **statistical risk register (SRR)** which this program would develop would be an extension of this core concept. In place of first-order probability and consequence estimates, high-fidelity and flexible probability distributions would instead be generated, rendering the end product highly informative and flexible.

Data Collection

Archival Work and Database Construction

The foundation of this project would be the collection and digitization of the records listed in the previous section. This phase of the work would require cooperation from data providers to issue approvals and provide access to archives.

As documents are retrieved and digitized, quantitative data and qualitative information should be organized into a database to collate and track evolving expenditure, cost estimate, and schedule information over the course of each project. The database should allow ready retrieval of data along a variety of dimensions, for example:

- Estimates of final total NSSS costs over time for a particular plant of interest.
- Number of labor strikes at each plant, grouped by FERC region.
- Cost increase as a percentage of total contract value for each turbine-related change order at all plants.

Establishing a consistent format for data organization will allow in-depth statistical analysis of information across projects, as well as the assembly of timelines showing evolving expectations and outcomes of each project.

Quality assurance on the transcription of the data should occur at this stage. Once document sets are fully digitized and the data has been vetted, each data provider should be given access to data from their own projects.

Risk Framework Development

The cornerstone of an effective database for this purpose should be a framework for categorizing cost increases, delays, and the causes thereof. Categorizing these events and outcomes allows them to be easily tracked and compared across projects, and allows similar but non-identical events to contribute to the development of a risk estimate for the event class (event classifications that are too narrow may have too few members each to produce meaningful frequency statistics).

Once sufficient documentation has been retrieved, the body of knowledge should be examined qualitatively to determine what broad categories of events are most common or most likely to be significant, and how those categories should be broken down in order to capture meaningful results without overly fragmenting the dataset. This would result in an umbrella structure where event classes include multiple varieties of subclasses, which each accrue their own data points but can be rolled up to the broader category if necessary. Additionally, subclasses should be parameterized using informative differentiating data about each occurrence. For example, an event class might be "delayed receipt of major item", with its subtypes parameterized by item, related plant system, item cost, length of delay, and position in the schedule. Individual occurrences could then be entered into the tracking system with all of the relevant information appropriately tagged. Finally, each event should be issued an event ID number, and linked to metadata about the project, utility, and timing of the event.

Data Analysis

The collection of detailed project data would permit the following types of analysis for the first time at this level of detail.

Disruption Frequency Analysis

Appropriate probability distributions can be generated on the basis of this data. Obtaining a sufficient number of project data sets is crucial for this step; because there are many parameters that may influence the probability of particular types of adverse events occurring, many observations for each event type will be needed. Within the framework established under the previous activity, each recorded instance of a project disruption should be categorized according to its type and parameters. Based on this event collection, as well as project parameters, multidimensional probability distributions for each event class should be developed.

In this stage, "risk chokepoints" would become apparent—activities or project stages in which risks are disproportionately likely, have an overly large impact, or both. These chokepoints should be targets for additional risk-reducing design and management preparedness, and would provide information about how advanced reactor designs differ in risk profile from conventional gigawatt-scale LWRs.

Event types should also be categorized by cause, particularly "external" versus "internal"/"acausal" events. For example, disruptions caused by supplier late delivery of critical components should be distinguished from disruptive field re-engineering due to an NRC action. This would allow the testing of hypotheses about the prevalence of externally-caused project disruptions, e.g. rework due to regulatory changes. It would also allow examination of various potential adjustments to the construction process; for example, a "robust supply chain" scenario where the probability of supplier-caused disruptions is diminished, or a "low unionization" scenario where probability and magnitude of labor strikes is minimal.

Net Impact Modeling

The distributions and consequence estimates developed in the previous activities should be rolled into a comprehensive stochastic impact model. Based on an input set of project parameters (e.g. technology, capacity, location, utility finances, regulatory environment), the model should generate a large population of sample projects with randomly-generated disruption events, and calculate their total final project costs. The distribution of cost outcomes for this population would in turn produce a spectrum of LCOE figures, as well as overall risk estimates. This type of Monte Carlo analysis would provide insight into the range of expected outcomes for nuclear projects having the given set of input parameters. Additionally, a utility financial risk model should be created to accept information about preexisting utility financial metrics and incorporate outcomes from the reactor-project MC simulation, in order to determine the distribution of financial outcomes for the firm. The event framework, frequency analysis, and outcome spectrum would make up the SRR, and would be used to simulate utility perception of and response to the risk posed by the project type under consideration.

Extrapolation to Future Designs

The risk chokepoints identified by this study may be impactful to the development of advanced reactor designs. One method for evaluating the financial and economic fitness of advanced reactor concepts currently under development is to identify how those designs have reduced or eliminated likelihoods or consequences at each risk chokepoint, or if certain design choices may exacerbate the same. This information would be valuable to developers, utilities, and private capital alike, to indicate whether those concepts' risk characteristics are more favorable than those of traditional LWRs, and to provide information for higher-fidelity cost and risk estimation of as-yet-unbuilt reactor types.

CONFIDENTIALITY

There are likely to be significant confidentiality concerns regarding this data. Precautions should be taken to ensure that no data is inappropriately shared or published. Appropriate nondisclosure agreements will need to be established, ensuring that results can still be shared provided that all identifying information is thoroughly scrubbed, and data and results are anonymized. Strict compartmentalization of data should be maintained: no utility or EPC should be given access to data from any other utility or EPC.

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