Fusion Power Plant Cost Modeling Uncertainties

Nousheen Nawal, Hanni Lux, *Member, IEEE*, Rhian Chapman, and James R. Cowan

***Abstract*— Being a novel technology, estimating costs for fusion power plants comes with large uncertainties. Cost uncertainties in prototypes arise from various sources and reduce with program maturity (including the selection of a site), technical and design maturity, as well as the maturity of the commercial strategy (e.g., make versus buy decisions and partnering decisions). In the early design phases, where not much detail is fixed, the cost is typically evaluated via analogy/comparator to existing technologies, which are typically associated with high uncertainties due to the innovative nature of fusion technology. Early cost estimates for fusion power plants are broken down using a top-level cost breakdown structure as this allows for cost uncertainty evaluation over the various fusion components. The STEP prototype fusion power plant is nearing the end of conceptual design with significant uncertainties but seeks to follow best practices to effectively manage costs. Best practice in cost estimating involves evaluating the base cost estimate, corresponding uncertainties, and project risks and correcting for optimism bias as defined by the Infrastructure and Project Authority (IPA). The overall objective is to illustrate the importance of uncertainty definition within fusion prototype/demonstration power plants and their impact on program costs.**

***Index Terms*— Costs, fusion power generation, uncertainty.**

I. Introduction

FUSION is an emerging energy technology that hopes to globally transform the energy sector once commercialized, with both government and private investment at an all-time high [1]. For fusion energy to attain recognition as a viable sustainable solution, it requires cost competitiveness. Many prototype/demonstrator fusion power plant programs are in their conceptual or early engineering design phase [2], [3], [4], which is an ideal time to influence the cost of the final product [5]. However, due to its first-of-a-kind (FOAK) nature and nascent supply chain, cost uncertainties are inevitably large. Therefore, it is prudent to understand their magnitude, distribution, and sources, as well as have a clear strategy to reduce these cost uncertainties as the respective programs mature.

Some works to estimate the costs of prototype/demonstrator/commercial fusion power plants have been published in the past [6], [7], [8], [9], [10], however, due to the early stages, no uncertainty evaluations for costs have been conducted. Typically uncertainty evaluation and propagation for fusion power plant design has been restricted to evaluating the impact of engineering or physics uncertainties on outturn performance if the plant was built in line with its current design [11], [12], [13], [14].

The STEP program, which aims to design and build a prototype fusion power plant that can provide net energy into the national grid of circa 100 MWe [15] is nearing the end of its conceptual design phase, transitioning into its engineering design. As such, there are significant design, engineering, construction, and hence cost uncertainties prevalent at this time.

We begin by discussing the various sources of uncertainties for large programs in Section II. We then consider the best practice of evaluating uncertainties in cost estimation and how they are expected to be reduced over a program's lifecycle in Section III. In Section IV, we discuss the application of cost uncertainties in STEP as an example of a current prototype fusion power plant program at the end of its conceptual design stage. We conclude in Section V.

II. Sources of Cost Uncertainties

To quantify these cost uncertainties at such an early stage of development, a strategic approach must be taken to first understand all the possible sources of uncertainty and their impact.

The AACE Class Estimate System [16] is an effective tool for managing cost uncertainties over time. While there is no universally defined industry standard for fusion cost estimation, it is necessary to recognize the AACE Class Estimate System's widespread use and acceptance in costing mega projects. We can draw parallels to the fission industry's Generation IV cost-estimating guidelines, where the AACE system has been extensively employed for costing [17]. This system categorizes project definition levels into five distinct classes, with Class 5 having the lowest level of definition and Class 1 having the highest. Initially, FOAK fusion projects at Class 5 rely on general benchmarks and expert opinions, leading to significant cost uncertainties. However, as the project progresses through Classes 4, 3, and 2, and ultimately reaches Class 1, the level of project definition and accuracy of cost estimation greatly improve. We can attribute this class system to sources to formulate a strategy and allow for effective management of cost uncertainties through a project's lifecycle.

A. Program Maturity

In FOAK fusion projects, uncertainties in cost estimation are notably influenced by the level of program maturity. At the

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TABLE I
PROGRAM MATURITY ESTIMATES CLASSIFICATION

Estimate classification	Class 5	Class 4	Class 3	Class 2	Class 1
Project description	General	Preliminary	Defined	Defined	Defined
Target operating model	General	Preliminary	Defined	Defined	Defined
Technology selection	General	Preliminary	Defined	Defined	Defined
Site location	General	Preliminary	Defined	Defined	Defined
Contracting model	General	General	Preliminary	Defined	Defined
Change and escalation strategies	None	Preliminary	Defined	Defined	Defined
Integrated project plan	None	Preliminary	Defined	Defined	Defined

early stages of a program, stakeholder expectations may not yet have been sufficiently defined, and early requirements are often subject to change as objectives and solutions emerge.

Program planning is the essential basis for effectively dealing with these uncertainties in a big project. Its main goal is to systematically advance program development. The program schedule plays a crucial role in estimating indirect costs associated with activities such as project management, administration, support services, and any other standing-army resource type. When there are delays or extensions in the project schedule, the duration over which such costs are borne also increases, leading to significant cost of time delays increases. Uncertainties related to other schedule changes can affect the overall cost estimation and budgeting process.

A prime example is the process of site selection. The selection of a suitable site for a fusion power plant involves geological, environmental, and regulatory considerations, which can introduce uncertainties in estimating costs and can vary widely between potential sites. A further classification of estimates is presented in Table I extracted from STEP's cost estimate uncertainty reduction strategy document.

B. Technical and Design Maturity

FOAK fusion projects, which involve early-stage technologies with low technology readiness levels (TRLs), face significant integration challenges due to the complex nature of plasma physics [18] and its interaction with materials, structures, and so on.

During the conceptual design phase, it is anticipated that cost estimation would be greater than the Class 5 level due to a lack of detailed design and clarity on system integration. As we transition toward the end of the detailed design phase to the construction phase, the expectation would be to achieve a Class 3 estimate. This phase would involve cost estimation based on the completion of all basic engineering documents, as well as starting preliminary mechanical and structural drawings. Given the unique FOAK nature of STEP, achieving a Class 1 estimate is unlikely. The primary challenge arises from the unprecedented characteristics of many high-cost components that have never been constructed, resulting in a limited foundation for cost estimation before manufacturing. A contributing factor is that STEP is planned to have detailed design and construction phases taking place simultaneously, further complicating the attainment of a Class 1 estimate due to the intricacies of the FOAK construction process. This is broken down into further detail below in Table II.

TABLE II
TECHNICAL AND DESIGN MATURITY CLASSIFICATION

Estimate classification	Class 5	Class 4	Class 3	Class 2	Class 1
Block flow diagrams	Started / Preliminary	Preliminary / Complete	Complete	Complete	Complete
Plot plans		Started	Preliminary / Complete	Complete	Complete
Soils and hydrology		Preliminary	Complete	Complete	Complete
Materials selection		Preliminary	Preliminary / Complete	Complete	Complete
Process flow diagrams		Started / Preliminary	Preliminary / Complete	Complete	Complete
Utility flow diagrams		Started / Preliminary	Preliminary / Complete	Complete	Complete
Piping and instrumentation diagrams		Started	Preliminary / Complete	Complete	Complete
Heat and material balances		Started	Preliminary / Complete	Complete	Complete
Process equipment lists		Started / Preliminary	Preliminary / Complete	Complete	Complete
Utility equipment lists		Started / Preliminary	Preliminary / Complete	Complete	Complete
Electrical one-line diagrams		Started / Preliminary	Preliminary / Complete	Complete	Complete
Specifications and data sheets		Started	Preliminary / Complete	Complete	Complete
General arrangement diagrams		Started	Preliminary / Complete	Complete	Complete
Spare parts listings		Started / Preliminary	Started / Preliminary	Preliminary	Complete
Mechanical drawings		Started	Started	Preliminary	Preliminary / Complete
Electrical drawings		Started	Started	Preliminary	Preliminary / Complete
Instrument and control system drawings		Started	Started	Preliminary	Preliminary / Complete
Civils / structural / site drawings		Started	Started	Preliminary	Preliminary / Complete

C. Commercial Strategy Maturity

While the impact of commercial strategy cost uncertainties may not be as pronounced as the prior two sources, they remain a necessary aspect to assess. The commercial strategy encompasses critical elements related to project procurement, partnership arrangements, contractual terms, and so on. In the early stages of a FOAK fusion power plant project, the supply chain may be nonexistent, underdeveloped, or lacking maturity. This poses challenges in accurately estimating the costs of components and materials, as reliable market data and pricing information may be limited. Large-scale FOAK projects often involve bespoke and/or long lead items, which are critical components or equipment requiring an extended lead time for manufacturing or delivery. The uncertainties associated with an immature supply chain can impact cost estimation and procurement planning. Table III defines the class requirements

TABLE III
COMMERCIAL STRATEGY MATURITY CLASSIFICATION

Estimate classification	Class 5	Class 4	Class 3	Class 2	Class 1
Procurement strategy	General	Preliminary	Defined	Defined	Defined
Procurement packaging strategy	None	Preliminary	Defined	Defined	Defined
Partnering arrangements	General	Preliminary	Defined	Defined	Defined
Terms and conditions	General	Preliminary	Defined	Defined	Defined
Incentivisation arrangements	General	Preliminary	Preliminary	Defined	Defined
Securities and guarantees	General	Preliminary	Defined	Defined	Defined

TABLE IV
ESTIMATE UNDERPINNING MATURITY CLASSIFICATION

Estimate classification	**Estimate underpinning**
Class 5	• Very low level of project definition • High level benchmarks • Expert opinions
Class 4	• Low level of project definition • Parametric cost data • Reference projects
Class 3	• Reasonable level of project definition • Unit cost line items • Detailed take-offs / bills of quantities • Supply chain prices
Class 2	• Good level of project definition • Unit cost line items • Detailed take-offs / bills of quantities • Supply chain prices
Class 1	• High level of project definition • Unit cost line items • Actual design quantities Contracted supply chain prices

at each stage of the cost uncertainty estimate taken from STEP's cost uncertainty reduction strategy document.

D. Estimate Underpinning

Cost estimation often relies on analogies and comparators to existing technologies. However, the inherent differences between fusion and other technologies introduce large uncertainties as analogous programs for a fusion power plant are practically nonexistent.

Consequently, when attempting to cost projects at the concept design phase, it is assumed that any estimates will have a substantial uncertainty range likely exceeding a "Class 5" uncertainty range. As the project progresses from initial stages, such as top-down costing, to more detailed phases like bottom-up costing, there is a notable reduction in uncertainties. This transition, marked by the development of a comprehensive cost estimate, represents a pivotal stage where uncertainties begin to take on a more distinct form. At this phase, uncertainties can be methodically characterized and broken down into a greater level of granularity.

Table IV provides an overview of estimate classifications of estimate underpinning characteristics, ranging from Class 5 with a very low level of project definition to Class 1 characterized by a high project definition.

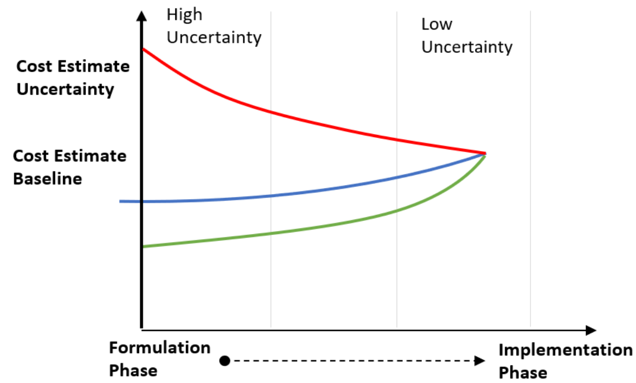

Fig. 1. Typical evolution of uncertainties in programs. The accuracy range is expected to reduce, while the base estimate typically increases [19].

During the early conceptual design phase, high uncertainties are common due to various factors stated (see Fig. 1). The absence of a detailed and mature schedule poses challenges in accurately estimating costs and timelines. Furthermore, the limited design and technical maturity of the fusion power plant at this stage introduce additional uncertainties related to the costs associated with developing and implementing novel technologies.

As the project progresses into the detailed design and construction phases, there is a gradual reduction in uncertainties. With the refinement of the design and the increasing technical maturity, there is a clearer understanding of the required components, materials, and construction processes. However, it is important to note that even during these phases, some level of uncertainty remains as unforeseen challenges may arise during construction or engineering design modifications.

As the project transitions toward plant operation, uncertainties are expected to decrease significantly. With a fully functional and operational fusion power plant, the project team gains experience, accumulates operational data, and can better estimate costs related to maintenance, fuel, and operational processes.

III. BEST PRACTICE OF REPORTING/EVALUATING UNCERTAINTIES IN COST ESTIMATION

A standard best practice cost estimate is built by combining the base estimate, cost estimating uncertainties, and the costed risk impact [5] as shown in Fig. 2. For megaprojects like fusion power plants, it is then prudent to correct the final value for any residual optimism bias, often determined through processes such as reference class forecasting [20].

The base estimate involves determining the expected cost of designing, manufacturing, and integrating a component within the fusion power plant. This estimation is based on factors such as material costs, labor costs, and engineering efforts. An uncertainty range will then be applied to each of these cost estimates. Cost uncertainties refer to the upper and lower cost ranges which are applied to the base estimate. They consider potential fluctuations and variations of cost due to the various sources of uncertainties, as discussed in Section II.

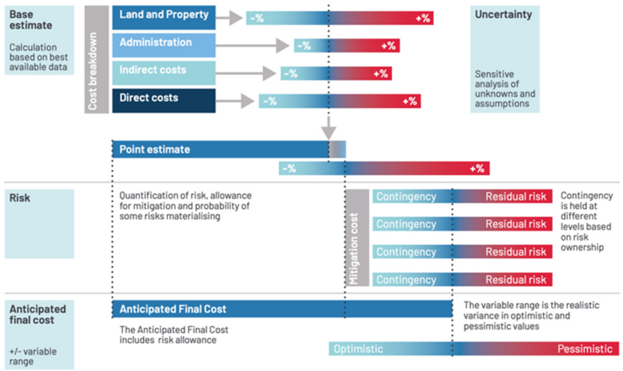

Fig. 2. IPA cost estimating guidance best practice buildup of anticipated final cost estimate and confidence range [5].

Accounting for uncertainties is crucial to ensure that the cost estimate remains within a realistic range. Risk represents the second layer of costs, visually depicted in Fig. 2. The costed risk impact refers to the potential negative effects that can impact the project's overall cost estimate. These risks are conditions that might lead to cost overruns. This can range from supply chain disruptions, manufacturing defects, or other unexpected events. It is important to note that cost estimates are subject to potential biases, such as optimism bias, which tend to underestimate costs. To address this, optimism bias correction is applied to the anticipated final cost. This is the final correction factor implemented as seen in Fig. 2 to help counterbalance the inherent tendency toward underestimating costs and ensure a more realistic and conservative estimate.

IV. Application of Cost Uncertainties in the STEP Program

As the STEP program is completing its conceptual design phase, it is gaining the maturity to evaluate the impact of the uncertainties of the individual cost accounts on the total program costs. So far, the program has been recording individual uncertainties without propagating them to the total costs and has even seen increases in cost uncertainty as the understanding of the design matured. As a result, there has not been sufficient confidence in the total program estimate so far and uncertainties are partially expected to be larger than the range expected for Class 5 estimates. This is in line with lessons learned from other programs (e.g., [21]), which find that "early-stage cost estimates are unreliable predictors of the eventual cost of megaprojects. This is valid across all nuclear technologies and large nonnuclear megaprojects."

Just like other fusion FOAK projects, STEP lacks benchmarking data due to its unique and innovative nature. Without comparable projects or historical data, it becomes challenging to estimate uncertainties based on industry norms or past performance. Uncertainties are often easier to estimate and propagate when supported by quantifiable data. As a result, while we have been able to identify ranges of uncertainties, it has been challenging to identify appropriate distribution functions. Consequently, sensitivity studies need to be carried out to understand the impact.

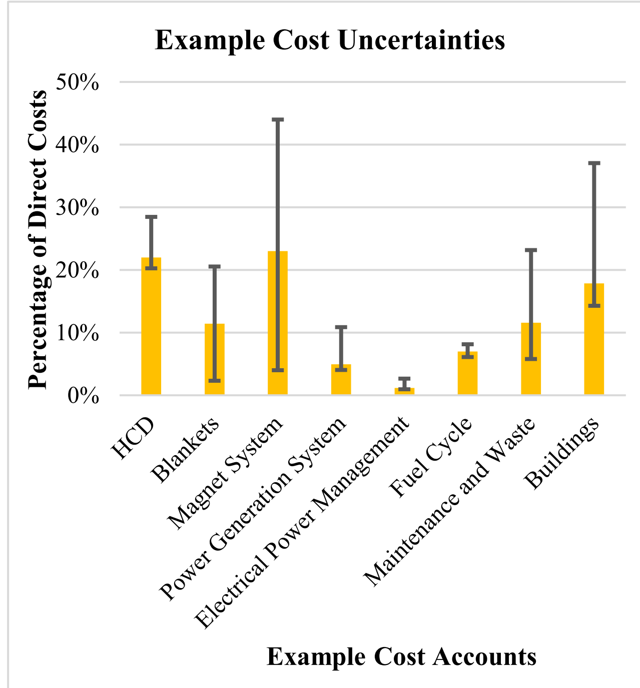

Fig. 3. Example uncertainties of selected reactor equipment cost account.

Fig. 3 presents an example of a cost account breakdown for the STEP project. The uncertainty ranges are depicted through error bars, populated using various methods such as standard deviation, triangular distribution, or the AACE class system, depending on the available cost modeling data. These cost accounts encompass various crucial aspects of the fusion project, and the variations in the size of the error bars reflect the diverse levels of uncertainty attributed to each component. Current calculations use the best available data. It is expected that future uncertainty assessments will have the capability to assign weights to individual input cost data points, considering the reliability or maturity of the source data, hence outputting a more representative range, however, the information that would support that weighting is not currently available. Thus, it is anticipated that some of these costs will ultimately lean toward the higher end of the range presented here.

The uncertainty ranges vary quite drastically across the different accounts. Magnets on STEP represent a focal point of significant cost uncertainties. These uncertainties stem from a complex interplay of factors, making magnets a challenging and volatile cost component. First, the technical complexity of fusion magnets is a primary driver. The engineering of the magnetic coils demands cutting-edge materials and manufacturing techniques, often with limited precedents. The resulting technological innovation introduces inherent uncertainties in design, performance, and, consequently, cost. Moreover, the uncertainty in material costs further exacerbates the issue.

Likewise, the Blanket has high uncertainties due to its low TRL. In the early stages of fusion development, these technologies are less mature and have limited operational experience, making it challenging to accurately estimate their costs.

The uncertainty range for the buildings account is significant, one of the key contributing factors is the absence of fusion-specific regulations that outline clear standards for the construction of fusion facilities. This regulatory gap means that fusion projects like STEP must navigate their building processes with less-established frameworks tailored to their specific needs. This creates larger-than-usual cost uncertainties in the building account.

Unlike the Magnets system and Blanket account, the electrical power area has a much smaller uncertainty range. Compared to cutting-edge fusion technologies like magnets or plasma confinement systems, electrical power systems generally involve lower technical complexity. Electrical components and materials, such as transformers, generators, and cables, are typically part of mature markets with stable pricing. Market fluctuations are less pronounced compared to specialized materials used in fusion magnets, contributing to reduced uncertainty in material costs.

As the STEP program advances through its conceptual design phase, it is gaining the ability to evaluate the influence of uncertainties on individual cost accounts. This variation in uncertainty ranges underscores the need for tailored cost management approaches for different fusion project components.

V. Conclusion

While multiple efforts have been made in the past to evaluate the costs of prototype/demonstrator/commercial fusion power plants, previous work has not evaluated or reported on the uncertainties in these cost estimates. As fusion power plant programs mature, it is essential to evaluate and communicate the accuracy range of their corresponding cost estimates and understand how they are expected to reduce over time.

It is best practice cost modeling to evaluate the base costs, corresponding uncertainties, and risks and apply optimism bias corrections. Sources for cost uncertainties include the technical and design maturity, the program maturity, the status of the commercial strategy as well as the accuracy of the underpinning estimate. All of these are expected to decrease over time, as the overall work on the different aspects progresses.

The STEP program is applying best practice cost-estimating methods including the evaluation of uncertainties. Throughout its conceptual design phase, it has experienced cost uncertainties increasing, as more was understood about the design. However, due to the still highly uncertain nature of the costs following the end of the conceptual design phase, it is difficult to determine the appropriate distributions of uncertainties making it difficult to determine corresponding P80 or P90 values. Therefore, currently, only ranges are being reported.

Due to the large uncertainties, the STEP program currently does not report total program costs but is using differential costing to support the decision-making process for design decisions to optimize the cost of the STEP prototype power plant, while it is building more confidence in its total program cost model. Going forward, the cost uncertainties are expected to decrease as the program, design, and commercial strategy mature.

To deliver cost estimates that assure the confidence of investors and other stakeholders, the fusion community needs to follow best practice cost-estimation techniques including evaluation and reporting of uncertainties.

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