Reference Class Forecasting and Its Application to Fusion Power Plant Cost Estimates

Chris Brown, Hanni Lux, *Member, IEEE*, and James R. Cowan

Abstract—**Developments in fusion energy technology and the aspiration to build and run commercial fusion energy power plants have seen the commencement of numerous publicly and privately funded projects in recent years. Megaprojects, like fusion power plants, by their very nature are inherently complex and risky, therefore, providing a robust cost estimate in the early stages is challenging. In the fusion sector, this is amplified by the fact that very little data exist on which to base an estimate due to the novel nature of the materials and technologies involved. A common phenomenon during the estimating phase of a new project is the concept of optimism bias (OB), where underestimation of time, cost, and risk can cause impacts on the baseline cost and schedule, leading to significant over-runs during the project lifetime. Reference class forecasting (RCF) is a method used to mitigate against these factors, based on using actual performance data in a reference class of comparable projects to improve forecasting accuracy. This article will discuss RCF, how it has been used in recent megaprojects, and how it is intended to be used in the Spherical Tokamak for Energy Production (STEP) program to provide a full program cost model for a prototype fusion energy plant.**

Index Terms—**Cost estimating, fusion power plant, optimism bias (OB), reference class forecasting (RCF), spherical tokamak for energy production (STEP).**

I. INTRODUCTION

AS THE nascent fusion energy sector grows its ambition to build and run commercial fusion power plants to support future energy requirements and to contribute to the net zero targets of governments around the globe, the number of megaprojects associated with fusion technology will increase [1], [2], [3], [4]. As a result, there will be increased scrutiny of the financial aspects of these megaprojects as stakeholders try to understand the commercial viability of a fusion power plant.

Cost estimates will therefore need to increase in accuracy, as we look to deliver value for money and return on investment, whether these be public or privately funded ventures.

Forecasters attempting to provide cost estimates for megaprojects face various challenges, including the complexity of the environment, the presence of uncertainty, and biases, especially at an early stage of concept maturity, where most fusion technologies currently sit.

Reference class forecasting (RCF) is an estimating methodology that aims to help forecasters mitigate the biases inherent in the cost estimation of projects by simply comparing the present situation with past situations that are similar [5]. RCF involves identifying a reference class of past cases that are relevant to the current situation and using the statistical properties of the reference class to make predictions about the future. RCF has been shown to be an effective method for improving forecasting accuracy in various domains [6], and this article will discuss how it is intended to be used in the U.K. Atomic Energy Authority (UKAEA) spherical Tokamak for energy production (STEP) program.

STEP is the flagship fusion program for the U.K. which aims to design and build a prototype fusion energy plant capable of delivering net electricity [4], with its mission to “deliver a U.K. prototype fusion energy plant, targeting 2040, and a path to commercial viability of fusion.” At the time of writing, STEP has recently passed a major concept design milestone with work moving toward the maturation of the design in the next four-year tranche.

II. WHY ARE MEGAPROJECTS DIFFICULT TO ESTIMATE?

Megaprojects, sometimes called “major programs,” are large-scale, complex ventures that typically cost more than one billion U.S. dollars, take many years to build, involve multiple public and private stakeholders, are transformational, and impact millions of people [7]. As such, they are more difficult to estimate for several reasons:

A. Uncertainty

Megaprojects often involve a high degree of uncertainty in terms of their scope, schedule, and costs. This can be due to factors such as unforeseen or novel technical challenges, regulatory requirements, and changing market conditions. This is especially true of first-of-a-kind fusion power plant endeavors.

B. Complexity

Megaprojects are often highly complex, with many different components and subsystems that must be integrated and coordinated. Complexity is not limited to technical aspects, but also includes people and interfaces. This makes it difficult to accurately estimate the time and resources required. Fusion power plants are highly integrated technologies, where changes in one area often impact multiple others in a nonlinear fashion.

C. Dependencies

Megaprojects typically involve many interfaces and stakeholders, including suppliers, contractors, and regulatory

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The authors are with Culham Science Centre, UKAEA (United Kingdom Atomic Energy Authority), Abingdon, OX14 3DB Oxfordshire, U.K. (e-mail: chris.brown@ukaea.uk).

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agencies. These stakeholders are predominant and can have a significant impact on the project timeline and costs, and their actions may be difficult to predict. Fusion power plants are typically multiparty programs that bring together multiple stakeholders from governments, regulators, private investors to multiple manufacturers, and construction companies.

D. Scale

Megaprojects are often much larger in scale than other types of projects, which can make it difficult to accurately estimate the resources required. Megaprojects cannot just be assumed to be linear in terms of scaling up or down from a starting point, it can be much more complex in practice. For example, the construction of a large infrastructure project may require thousands of workers and millions of pieces of equipment and requires excellent project management processes and skills to manage and coordinate.

It is therefore understandable that most megaprojects become their own separate entity to effectively manage such a large undertaking. In the example of the STEP program a new company, UKIFS, a subsidiary of UKAEA, has been created for this very reason.

While many private fusion companies aim for small plant sizes from micro-reactors of 5 KWe to small reactors of up to several hundred MWe [1], publicly funded programs typically assume that fusion reactors have an economy of scale and aim for GW scale power plants [8], [9]. Nevertheless, even ∼100 MW fusion power plants can still be expected to have sufficiently large scale to be considered a Megaproject.

The challenge of providing cost estimates for megaprojects, especially in the early stages, is discussed in detail in MIT's study from 2018 [10]: The following conclusion is stated: "Early-stage cost estimates are unreliable predictors of the eventual cost of megaprojects. This is valid across all nuclear technologies and also large nonnuclear megaprojects." Future fusion megaprojects would certainly fall into this grouping.

Fig. 1 uses the data discovered in the study to show that as designs mature and incorporate more detail, cost uncertainty decreases but (more importantly) actual cost increases significantly [10]. A database of 318 industrial megaprojects was used in this analysis; blue datapoints indicate the mean from all projects and variance bars indicate the standard deviation, at varying design maturity classes using the AACE estimating classes [11]. The highlighted examples show data from fission technologies e.g., AP-1000 Westinghouse PWR Fission Power Plant.

Based on independent research performed for STEP, common trends emerge that drive cost increase as follows:

1) Increase in material and labor costs;
2) Underestimating complex engineering requirements associated with the project;
3) Over-optimistic bias with regard to the initial estimate;
4) Initial estimate not based on eventual project scope;
5) Design changes throughout construction incur additional design costs and incurring additional costs due to timeframe extension.

In summary, the sheer size and complexity of megaprojects make them much more difficult to estimate correctly. The effect of multiple stakeholders and interfaces combine to create feedback that is unpredictable. Analysis of relevant data in [10] highlights the trend of early-stage cost estimates being unreliable predictors of the eventual final cost of megaprojects; it is clear that there is a need to improve our cost estimation techniques in megaprojects. Therefore, an estimating methodology such as RCF could be effective to help mitigate the risks in providing estimates for such large-scale projects, of which fusion power plants are one example.

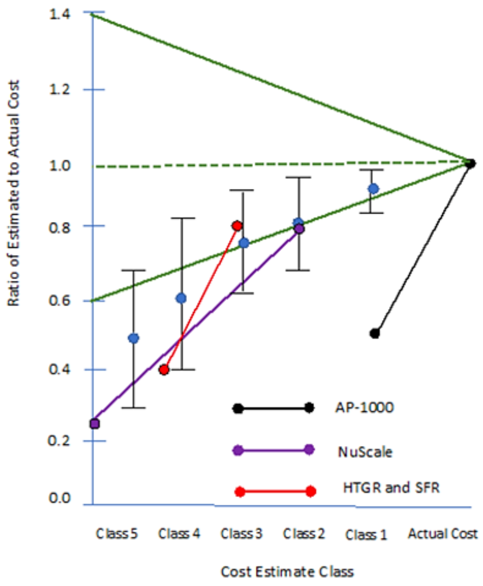

Fig. 1. Cost estimation trends in megaprojects.

III. RCF Methodology

RCF is a method of forecasting that involves identifying a reference class of similar events and analyzing their historical data to predict the likelihood of future outcomes. The reference class is a set of past events that are similar in relevant respects to the event being predicted. For example, if we want to predict the outcome of an engineering project, we will look at the historical data of similar engineering projects in terms of scope, budget, and timeline; and use this data as a comparison for our new project.

RCF was first introduced by Kahneman and Tversky [5]. The authors defined RCF as "the use of similarity-based reasoning to predict an unknown quantity or outcome."

Kahneman and Tversky [5] found human judgment to be generally optimistic due to overconfidence and insufficient with regard to distributional information. Thus, people will underestimate the costs, completion times, and risks of planned actions, whereas they will overestimate the benefits of the same actions. Lovallo and Kahneman [12] call such common behavior the "planning fallacy" and argue that it stems from actors taking an "inside view," focusing on the constituents of the specific planned action rather than on the outcomes of similar already completed actions.

The RCF approach attempts to mitigate behavioral biases, such as optimism bias (OB), by taking the "outside view." It uses a database of actual performance of comparable past projects within a given reference class to provide an objective reference point for the cost forecast of a current project [13].

OB is a cognitive bias that causes people to overestimate the likelihood of positive events and underestimate the likelihood of negative events. This bias can have significant implications for decision-making, as it can lead individuals to make overly optimistic or unrealistic predictions about the future.

In practice, there is no "standard" RCF code of practice. Variations exist in how the approach is applied.

The main challenge for applying the RCF method is the accumulation of a sample of similar projects with a large enough sample size and accurate cost information. It may take a very long time to develop such a database [14]. Given that no fusion power plants have previously been built and only a limited number of fusion experiments can be considered as megaprojects, to gain relevant statistics, one has to use a reference class that contains nonfusion projects with similar novelty and complexity as comparators. If the program has access to more detailed data like that available for other industries e.g., rail [15], more detailed analysis can be performed, but this is challenging to find in comparator projects for fusion power plants. The problem is further exacerbated by the fact that often data are only available for cost estimates of publicly funded programs at final investment decision (FID) versus actual outturn costs, if at all. This prevents RCF being applicable in the earlier stages of the program prior to FID.

More specifically, RCF for a particular project requires the following steps [16], [17].

A. Select a Reference Class

Identification of a relevant reference class of past, similar projects. The class must be broad enough to be statistically meaningful but narrow enough to be truly comparable with the project at hand. For fusion programs, comparators of similar scale would be other power plants, while projects of similar novelty might be other first-of-a-kind research endeavors like CERN, ITER, or ESS. Other large-scale projects like the Olympic Games can also be considered due to their uniqueness.

B. Assess the Distribution of Outcomes

Establishing a probability distribution for the selected reference class. This requires access to credible, empirical data for a sufficient number of projects within the reference class to make statistically meaningful conclusions. Appropriate data are not necessarily publicly available and therefore depend on the specific data the program has access to. Intellectual property for such data sets in sufficient statistical numbers is typically held by specialized consultancy companies like Foresight Analytics or Oxford Global Projects.

C. Make an Intuitive Prediction of Your Project's Position in the Distribution

Predicting where the specific project lies within the reference class distribution to establish the most likely outcome for the specific project. Because this intuitive estimate is likely to be biased by the decision maker, the final two steps are intended to adjust the estimate to improve accuracy. Identifying risks leading to OB can be helpful to understand how much OB might be in the estimate. The U.K. government's supplementary green book guidance on OB gives some clear instructions on how this might be applied [18].

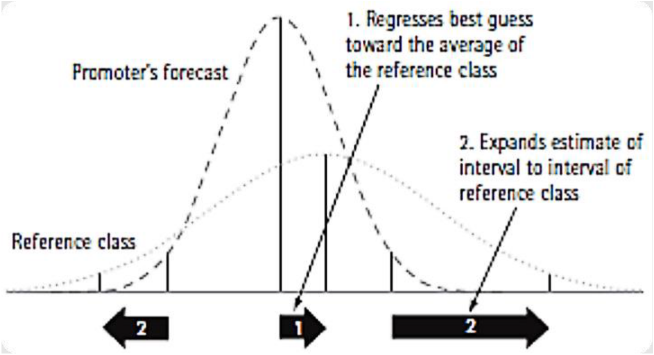

Fig. 2. What RCF does, in statisticians' language [19].

D. Assess the Reliability of Your Prediction

The intention of this step is to gauge the reliability of the forecast made above, by estimating the correlation between the forecast and the actual outcome, expressed at a coefficient between 0 and 1. This can be based on available data, for example, how well past predictions have matched the actual outcome or more subjective estimates of predictability.

E. Correct the Intuitive Estimates

Due to biases, the intuitive estimate will likely be optimistic. This final step adjusts the estimate toward the average based on the analysis of predictability above; the less reliable the prediction, the more the estimate needs to be regressed toward the mean.

Fig. 2 shows what RCF does in statisticians' language. First, RCF regresses the best guess of the conventional forecast—here the project promoters' forecast, indicated by the dashed curve—toward the average of the reference class. The distribution of outcomes in the reference class is indicated by the dotted curve. Second, RCF expands the estimate of the interval in the conventional forecast to the interval of the reference class [19].

Overall, RCF is a powerful tool that can help project teams estimate the likelihood of success or failure for a current project. By looking at similar projects in the past, project teams can make more informed decisions about budget, timeline, and risk management.

RCF can lead to more accurate predictions and decisions, but it can also lead to overconfidence if the past data and experience do not accurately reflect the current situation. Similarly, OB can lead to positive outcomes, such as motivation and confidence, but it can also lead to unrealistic expectations and poor decision-making.

IV. EXAMPLES OF RCF IN PRACTICE

Whereas Kahneman and Tversky [5] developed the theories of RCF, Flyvbjerg et al. [20] developed the method for its practical use in policy and planning, which was published as an official Guidance Document. Below, we summarize a few examples of RCF in large infrastructure projects that have some commonality with fusion power plant programs in terms of size, complexity, and impact.

The first instance of RCF in practice is described in [21]. This forecast was part of a review of the Edinburgh Tram

Line 2 business case, which was carried out in October 2004 by Ove Arup and Partners Scotland. At the time, the project was forecast to cost a total of £320 million, of which £64 million (25%) was allocated for contingency. Using the newly implemented RCF guidelines, they calculated the 80th percentile value for total capital costs to be £400 million (57% contingency). Similarly, they calculated the 50th percentile value to be £357 million, (40% contingency). The review further acknowledged that the reference class forecasts were likely to be too low because the guidelines recommended that the uplifts should be applied at the time of the decision to build, which the project had not yet reached, and that the risks, therefore, would be substantially higher at this early business case stage. On this basis, the review concluded that the forecast costs could have been underestimated. The Edinburgh Tram Line 2 opened three years late in May 2014 with a final outturn cost of £776 million, which equals £628 million when adjusted to 2004 prices [22].

Following the Edinburgh Tram project, RCF has been used by the U.K. government's Infrastructure and Projects Authority (IPA) as part of its project assurance process.

By using RCF, the U.K. government aims to improve the accuracy of project cost and time estimates, reduce the risk of cost overruns and delays, and ensure that taxpayers' money is used effectively. This approach has been used in several high-profile projects, including the Crossrail railway project in London and the High Speed 2 (HS2) rail service program.

A. Crossrail

Crossrail is a large, complex program to run new, direct rail services between Reading and Heathrow Airport at the western ends of the railway, to Shenfield in Essex and Abbey Wood in south-east London at the eastern ends. When complete, the railway will be around 73 miles (118 km long), stopping at more than 40 stations, including ten new stations and 26 miles (42 km) of new tunnels [23].

The initial cost estimate released in 2010 was £14.8bn. Due to multiple delays and cost increases, this was revised in 2019 to £17.6bn. A final estimate was given in 2021 of £18.9bn. This equates to a circa £4.1bn overrun, or a cost increase of 128%. In terms of schedule, the initial opening date of December 2018 has slipped to 2023 for full services [24].

"Early in its development, Crossrail was innovative in its rejection of OB in favor of Quantitative Risk Assessment (QRA) techniques. This resulted in Crossrail's reporting of Anticipated Final Crossrail Direct Cost (AFCDC) at P50 and P95." [25] Considering the outcome of the project, it can be argued that this rejecting a RCF approach for a more traditional QRA assessment may have contributed to the cost and schedule over-runs.

Causes for cost and schedule increases are described in [24], however, it is clear that cognitive biases were inherent in the project, especially during the 2015–2019 period when the project began to slip.

Post 2019, a new management team was appointed, and various measures were put in place, including RCF assessments and financial incentives. However, these ultimately had limited success due to the new management team uncovering various unknown problems and additional work [24].

B. High Speed 2 (HS2)

High Speed 2 is the ambitious program to create a new high-speed rail service from London to Manchester and Leeds, via Birmingham and the East Midlands. The program is split into three phases; Phase 1 between London Euston and the West Midland due 2026; Phase 2a between the West Midlands and Crewe due 2027; and Phase 2b completing the full network to Manchester and Leeds due 2033.

From the initial 2011 Economic Case, the cost estimate for HS2 has spiraled from £48bn to £125bn for the 2020 Full Business Case, a cost overrun of 260% [26].

RCF was used to set the £40bn target cost and £45bn funding envelope for Phase 1 [27]. The RCF was carried out by Oxford Global Projects, using a dataset of 526 projects. The Department complemented the RCF analysis with HS2 Ltd.'s quantitative cost risk assessment. The £45bn funding envelope is based on RCF at the P75 delivery confidence, which added approximately 37% to costs to go. This equates to £10bn of contingency and would provide for sufficient funding for potential cost overruns in 75% of the reference class sample. The £40bn target cost is calculated by taking the Phase One point estimate (£34.7bn) and adding contingency based on a P50 delivery confidence from the reference class forecast, an 18% adjustment on the costs to go, approximately £5bn [28], [29].

OB has been set at 40% for HS2 Phase 2 [30], which would seem to be low in relative terms if compared to other infrastructure projects in the same reference class. Future RCF for Phase 2 will clarify whether this assumption proved to be correct; however, recommendations in [26] suggest that over-optimistic cost estimates and OB are still inherent problems.

These examples show how RCF can be used in practice in a mature sector such as infrastructure and railways but cannot guarantee its applicability or success in the fusion field. Section V discusses how RCF is proposed to be used on STEP and examines analysis undertaken to show how this can be valuable in mitigating risks in the early-stage cost estimation of future fusion megaprojects.

V. USE ON STEP PROJECT

STEP is a UKAEA program that will demonstrate the ability to generate net electricity from fusion [4]. It uses RCF as part of its best practice approach to costing fusion power plants.

In 2023, STEP became part of the U.K. Government Major Projects Portfolio (GMPP). GMPP comprises the largest, most innovative, and highest risk projects and programs delivered by the U.K. government. Projects on the GMPP receive independent review and assurance from the IPA. As stated in IPA's Principles for Project Success, RCF is a requirement of all GMPP projects as part of its assurance processes and is mandated in The Green Book guidance issued by HM Treasury.

The STEP program has commissioned work by a private company to determine relevant reference classes that can be applied to their cost estimating models. A reference class of more than 250 global projects worth over $600 billion was collected across numerous project types and sectors.

As no directly relevant fusion reference class is available, due to the maturity of technologies and availability of relevant

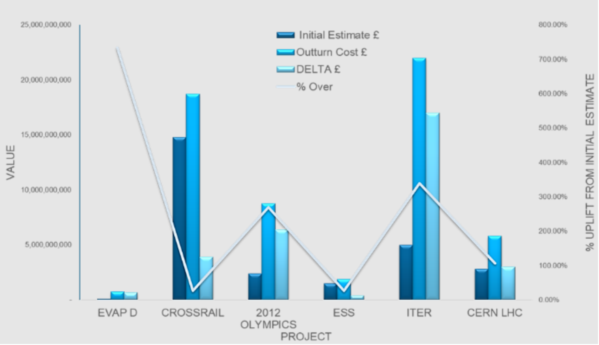

Fig. 3. Comparison of financial performance of selected projects in monetary value and percentage uplift.

data, this reference class was based on large-scale projects with high degrees of technical complexity in related fields such as nuclear power, space, big science, and first of a kind project.

Based on the techniques described in Section IV of this article, the output of the analysis gave the STEP program useful datasets and output data including P50 and P70 Cost Overrun and Time Overrun percentages that can be used to adjust future cost estimates. Additional scope focused on analysis of positive and negative performance throughout the reference class to determine levers for improving performance. A number of recommendations were provided which will help inform the future activities of STEP, including designing for modularization and utilizing tested technologies where possible. Future work will focus on analysis of the best and worst performing projects i.e., <P20 and >P70 overrun cases, to identify strategies where we can mitigate common risks and realize common benefits.

Unfortunately, the data supporting the analysis is confidential, and therefore, more detailed information cannot be provided in this article.

In addition to this procured service, supporting work was performed by the STEP team using publicly available data as a validation exercise. Initial research was undertaken to discover programs that match the defined criteria, i.e., similar scale, complexity, and novelty. Exact matches are difficult to locate, each program used for comparison must be considered in accordance with their own conditions of development and execution when being used to apply an adjustment to the STEP program estimate. The projects selected was done so on the basis that they were either large-scale endeavors, highly complex, and/or technically challenging or FOAK, and allowed access to the relevant cost data.

Fig. 3 shows the output from the analysis described above. It compares the initial estimate (the cost estimate stated in the business case or tender at contract award, the "FID"), outturn cost (the final cost of the project, or forecast final cost in the case of ongoing projects), and % uplift (variation) from initial project estimate to final outturn cost.

The results of this analysis determined a percentage increase from the initial estimate of 118% across the reference class, rising to 220% in the more scientific/FOAK-type projects (CERN, ITER, ESS).

These data are based on a very small subset and should not be considered a large enough range to be suitable for a standard reference class; guidance suggests a sample size of 20 to 30 projects minimum. In this example, the result of 220% is overly dominated by the data from the ITER project across such a small sample.

However, it suggests that typical fusion power plant projects might consider applying an uplift in excess of 100% to their initial cost estimates, possibly even higher in the early stages of design.

Further lessons learned from fusion-specific cost estimates come from the NSCX program [31] that was canceled due to significant cost over runs in relation to externally validated, early estimates (post-concept design, but preprototype manufacturing trials) due to its FOAK nature and massive underestimation about the amount of rework required in manufacturing to meet the high-quality requirements of the design. Suggesting that other fusion FOAK endeavors can easily suffer similar types of OB, without the application of mitigation techniques such as RCF.

VI. CONCLUSION

RCF and its potential to mitigate biases can have a significant impact on the accuracy of cost estimates. While RCF can help to reduce uncertainty and risk by providing decision-makers with empirical evidence based on past experiences, behavioral biases such as OB can lead to overconfidence and unrealistic expectations. Therefore, it is essential for estimators and decision-makers to be aware of both concepts and to use RCF as a tool to counteract bias inherent in the estimating process. By doing so, they can make more informed decisions that are based on evidence and avoid these pitfalls.

RCF can be a powerful tool in the armory of cost estimators to help avoid underestimation of costs in total program cost forecasts, especially in the early stages of megaprojects.

However, RCF is not without its limitations. Practitioners should be aware of these limitations and take steps to ensure that their predictions are as accurate as possible by benchmarking or validating their results.

In the U.K., RCF has been used in an increasing number of cases for publicly funded projects overseen by the IPA. Experience gained in these applications should be collated and should be used to help the production of cost estimates for the STEP project.

Initial research undertaken by the STEP program has identified relevant, but not directly comparable, reference classes that can be applied to fusion projects. The data suggests that typical fusion power plant projects might consider applying an uplift in excess of 100% to their initial cost estimates, possibly even higher in the early stages of design. By continuing to liaise with industry and government, STEP can drive best practice and build and maintain the most representative reference class available.

At present, the use of RCF in fusion applications cannot be based on direct comparisons with other fusion projects, as no direct datasets are available. Therefore, it is essential that the reference classes selected for fusion applications are suitable and validated until such a time exists that directly relevant fusion data sets exist. Clearly, this will require a collaborative approach from all interested parties and cooperation between private and publicly funded organizations.

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Chris Brown received the B.Sc. (Hons.) degree in aerospace business systems from the University of Salford, Salford, U.K., in 2007.

He has worked in various project management and controls roles, including the Project Controls Manager in the Nuclear and Defense sector and the Senior Cost Controller in the Oil and Gas sector. He currently works as the Fusion Cost Integrator responsible for the development of cost models for the STEP Program at U.K. Atomic Energy Authority (UKAEA), Abingdon, U.K.

Mr. Brown is a member of The Association of Cost Engineers (ACostE).

Hanni Lux (Member, IEEE) received the Diploma degree in physics from the University of Heidelberg, Heidelberg, Germany, in 2007, and the Ph.D. degree in theoretical astrophysics from the University of Zurich, Zürich, Switzerland, in 2010.

She currently leads the cost modeling team of the STEP program at U.K. Atomic Energy Authority (UKAEA), Abingdon, U.K. She joined UKAEA in 2013 and has held various roles covering fusion power plant integration and cost aspects. Prior to joining UKAEA, she has held a post-doctoral position in theoretical astrophysics with the University of Nottingham, Nottingham, U.K.

Dr. Lux holds a chartership with the Institute of Physics.

James R. Cowan received the B.Eng. (Hons.) degree in materials science and engineering and the Ph.D. degree from the University of Birmingham, Birmingham, U.K., in 1994 and 1998, respectively.

After early years, working in the civil nuclear power industry, he moved to the U.K. Ministry of Defense, where he held senior positions leading major programs and projects. He is currently the Director of Program Development for STEP within UKAEA.

Dr. Cowan is a Chartered Project Professional, a member of the APM, U.K. Infrastructure and Projects Authority high-risk independent review team leader, and U.K. Major Projects Leadership Academy graduate. He is also Chartered Engineer and member of the Institute of Materials, Minerals and Mining.