Nuclear Engineering and Design 243 (2012) 120–134

Contents lists available at SciVerse ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Minimizing the economic cost and risk to Accelerator-Driven Subcritical Reactor technology. Part 2: The case of designing for flexibility

Michel-Alexandre Cardin[a,*], Steven J. Steer[b], William J. Nuttall[b,c], Geoffrey T. Parks[b], Leonardo V.N. Gonçalves[b], Richard de Neufville[d]

[a] Department of Industrial and Systems Engineering, E1A #06-25, National University of Singapore, 117576, Singapore
[b] Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, United Kingdom
[c] Judge Business School, University of Cambridge, Cambridge CB2 1AG, United Kingdom
[d] Engineering Systems Division, E40-245, Massachusetts Institute of Technology, Cambridge, MA 02139, United States

ARTICLE INFO

Article history:
Received 16 February 2011
Received in revised form
20 November 2011
Accepted 21 November 2011

ABSTRACT

This paper presents a simple, systematic, and integrated methodology to analyse the expected Levelised Cost Of Electricity (LCOE) generation of a new nuclear technology facing significant technological uncertainty. It shows that flexibility in the design and deployment strategy of a demonstration commercial thorium-fuelled Accelerator-Driven Subcritical Reactor (ADSR) park significantly reduces the expected LCOE. The methodology recognizes early in the conceptual design a range of possible technological outcomes for the ADSR accelerator system. It suggests appropriate flexibility "on" and "in" the first-of-a-kind design to modify the demonstration park development path in light of uncertainty realizations. It then incorporates these uncertainties and flexibilities in the design evaluation mechanism. The methodology improves existing approaches for design and engineering decision-making, providing guidance for government support for a new, secure, clean, and publicly acceptable alternative technology for power generation.

1. Introduction

Thorium-fuelled Accelerator-Driven Subcritical Reactor (ADSR) technology is a promising avenue for the transmutation of radioactive wastes (Bowman et al., 1992; Foster, 1974), and for secure, low-emission, and more publicly acceptable power generation (Carminati et al., 1993). It consists of a nuclear reactor core operating subcritically, and a high-power proton accelerator that bombards a spallation target within the reactor core to generate neutrons. These externally supplied neutrons supplement the reactor's own neutron population and sustains a fission chain reaction, as in Fig. 1. This technology offers new opportunities to governments concerned with limiting CO_2 emissions, reducing risks associated with nuclear weapons proliferation and geological waste disposal, and sustaining prosperous economic development. In countries with considerable thorium reserves (e.g. India), it has the potential to capture a non-trivial segment of the growing electricity market. In other countries, it can help diversify the portfolio of low CO_2-emitting technologies.

Developing thorium-fuelled ADSR technology promises to be technically challenging, economically risky, and capital-intensive. Traditional nuclear power technology demands a large capital cost (Pouret et al., 2009), and requires many years of pre-development, construction, and testing before providing online capacity. An ADSR's further requirement of high-powered accelerator technology will demand additional capital commitment, and will therefore involve significant extra financial uncertainty. Given the high upfront cost, one needs a realistic and reliable picture about the expected returns, one that explicitly recognizes how the first-of-a-kind demonstration of the technology might perform.

There is much uncertainty associated with how technology will develop during the initial deployment phase of a first-of-a-kind ADSR demonstrator. This uncertainty will ultimately affect the Levelised Cost Of Electricity (LCOE) generation, which is a useful metric for evaluating economic performance and the value that a project is expected to return. One concern unique to ADSRs compared to other nuclear technology relates to the reliability of the accelerator supplying the proton-beam. If an unplanned shutdown of an accelerator leads to an ADSR shutdown, costs will be incurred due to failing to supply the electricity grid (Steer et al., 2009). Alternatively if unplanned shutdowns are eliminated through spending additional time performing maintenance on the accelerator, there is less time to schedule electricity generation and sales.

* Corresponding author. Tel.: +65 6516 5387; fax: +65 6777 1434.
E-mail addresses: macardin@nus.edu.sg (M.-A. Cardin), stevenjsteer@googlemail.com (S.J. Steer), wjn21@cam.ac.uk (W.J. Nuttall), gtp10@cam.ac.uk (G.T. Parks), ardent@mit.edu (R. de Neufville).

0029-5493/$ – see front matter
doi:10.1016/j.nucengdes.2011.11.026

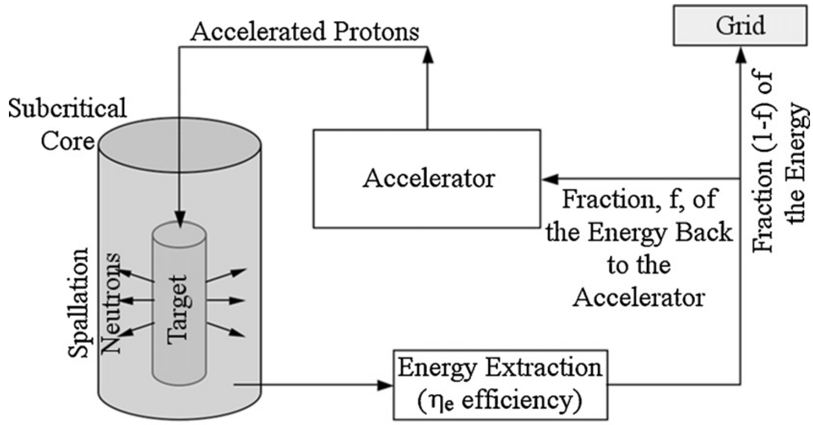

Fig. 1. Conceptual representation of an ADSR system for power generation.

Adapted from Rubbia et al. (1995).

To address these issues, this paper introduces and applies a simple, systematic, and integrated methodology to evaluate design and deployment strategies for innovative systems facing significant technological uncertainty. The starting point of the methodology for ADSRs is the technical design descriptions of a first-of-a-kind ADSR system offered in the companion paper by Steer et al. (2012). The methodology enables engineers and decision-makers to: (1) recognize explicitly uncertainty sources affecting the expected performance of the system; (2) incorporate the concept of flexibility in design and management with the goal of improving performance; and (3) evaluate the design space based on expected economic impact, to guide decision-making for large-scale investment and deployment.

The integrated methodology has been applied to investigate the hypothesis that inserting flexibility early in the conceptual design of an ADSR can improve the expected economic performance while testing and validating the technology. One anticipates that flexibility will lower the expected development and deployment cost of the system. The methodology builds upon and extends standard practice for design and decision-making in engineering by considering a priori a range of uncertain outcomes affecting costs, and adequate flexible responses. This approach differs from sensitivity analyses performed after an initial design is selected. It recognizes intelligent design and pro-active system management as uncertainty unfolds. The methodology provides a framework for evaluating designs, and assessing the expected value of flexibility so it can be compared to the cost of acquiring the flexibility.

The remainder of the paper is structured as follows. Section 2 provides an overview of related work in flexibility/real options analysis in an engineering context, together with previous work specifically focusing on the nuclear sector. Section 3 explains the integrated methodology, and Section 4 follows with an example application to the deployment of a demonstration commercial ADSR park. Section 5 concludes by discussing modeling assumptions and limitations, as well as findings. It also provides guidance for future work.

2. Related work

2.1. Flexibility in engineering design/real options

Flexibility in engineering design enables a system to change easily in the face of uncertainty (Fricke and Schulz, 2005). It is associated to the concept of real options, providing the "right, but not the obligation, to change a project in the face of uncertainty" (Trigeorgis, 1996). Real options "on" a project tend to involve higher-level managerial decisions such as abandoning, deferring until favorable market conditions arise, and investing in research and development (R&D) (Trigeorgis, 1996). Real options "in" a project include strategies like expanding/contracting/reducing capacity, deploying capacity over time, switching inputs/outputs, and/or mixing the above. They differ from real options "on" projects because they require careful engineering of system components, or possibly changes in their design to enable the flexibilities in operation (Wang and de Neufville, 2005). To be captured they need to be considered in the early conceptual design phase.

The real options analysis (ROA) literature typically focuses on the economic valuation of flexibility (Dixit and Pindyck, 1994; Myers, 1977; Trigeorgis, 1996). It builds upon the theory of financial options developed by Black and Scholes (1973) and Cox et al. (1979). Many studies have shown that flexibility in engineering projects can bring expected performance improvements ranging between 10% and 30% compared to standard design and evaluation methods (Amram and Kulatilaka, 1999; Copeland and Antikarov, 2003; de Neufville and Scholtes, 2011). Expected performance improvements arise by affecting the distribution of system responses, rather than optimizing a pinpoint design for a set of deterministic projections. Flexibility reduces the effect from downside, risky scenarios, while positioning the system to capitalize on upside, favorable opportunities. For example, Pindyck (1993) showed that additional economic value exists when managers recognize the flexibility to abandon construction of a new nuclear plant if technology and cost evolve unfavorably. This strategy protects from downside uncertainties, which can only be resolved once the irreversible investment is made. Examples in other industries include: strategically phasing the development of airport terminals over time (de Neufville and Odoni, 2003), designing offshore platforms for future capacity expansion (Jablonowski et al., 2008), adapting supply chains flexibly to uncertain currency exchange rates (Nembhard et al., 2005), etc.

It is important to consider uncertainty and flexibility early and systematically in the conceptual design phases of engineering systems. Design rigidity and relying too much on–sometimes over optimistic–deterministic projections of future conditions may contribute to the failure of an engineering system. This was the case for the Iridium satellite-based cell phone system, which filed for bankruptcy in 1999. The 77 Low Earth Orbit (LEO) satellite infrastructure, developed for the cost of U.S.$4 billion, enabled phone calls anywhere on the planet. The technology met its design goals; however, the design and management processes were centered on optimistic demand projections. This led to a rapid deployment strategy of the entire constellation between May 1997 and May 1998 (MacCormack and Herman, 2001). The projected demand did