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Minimising the economic cost and risk to accelerator-driven subcritical reactor technology: The case of designing for flexibility: Part 1

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

[a] Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, United Kingdom
[b] Department of Industrial and Systems Engineering, E1A #06-25, National University of Singapore, 117576, Singapore
[c] Judge Business School, University of Cambridge, Cambridge CB2 1AG, United Kingdom

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ABSTRACT

Demonstrating the generation of electricity for commercial markets with accelerator-driven subcritical reactor (ADSR) technology will incur substantial financial risk. This risk will arise from traditional uncertainties associated with the construction of nuclear power stations and also from new technology uncertainties such as the reliability of the required accelerator system. The sensitivity of the economic value of ADSRs to the reliability of the accelerator system is assessed. Using linear accelerators as an example of choice for the accelerator technology, the economic assessment considers an ADSR with either one or two accelerators driving it. The extent to which a second accelerator improves the accelerator system reliability is determined, as are the costs for that reliability improvement. Two flexible designs for the accelerator system are also considered, derived from the real options analysis technique. One seeks to achieve the benefits of both the single and dual accelerator ADSR configurations through initially planning to build a second accelerator, but only actually constructing it once it is determined to be economically beneficial to do so. The other builds and tests an accelerator before committing to constructing a reactor. Finally, a phased multiple-reactor park with an integrated system of accelerators is suggested and discussed. The park uses the principles of redundancy as for the Dual accelerator ADSR and flexibility as for the real options design, but for a lower cost per unit of electricity produced.

1. Introduction

In an attempt to meet energy needs in a responsible and sustainable way, a revolutionary nuclear reactor concept is having its engineering feasibility re-assessed. The design in question is the accelerator-driven subcritical reactor (ADSR), the concept for which dates back to the 1990s (Bowman et al., 1992; Carminati et al., 1993). If hopes for ADSRs are fulfilled then they will provide the world with electricity while: emitting minimal amounts of CO_2; ensuring a high level of safety during operation due to the use of an accelerator and a subcritical reactor core; achieving a significant reduction in backend radioactive waste compared to contemporary reactors – they may even consume waste from other reactors; and extending the consumption time of the world's uranium and thorium resources by multiple orders of magnitude. Inevitably a power station that promises so many benefits is not without its challenges. Multiple aspects of the engineering requirements of the design are the subject of challenging Research and Development (R&D) programmes (ENEA, 2001); chief areas of concern are the reliability of the accelerator system, the reliability of the beam target (the interface between the accelerator and reactor core) and long-term corrosion of the steel structure due to the presence of heavy liquid metal. A poor outcome from this R&D would be the finding that the design requirements of ADSRs are so extreme that they are untenably expensive.

In the commercial electricity market, all the nuclear power stations ever constructed have self-sustained fission reactions during operation – they are all critical reactors. When a critical reactor is operating, electricity is generated. For the ADSR (a subcritical reactor) only when the nuclear core and its accelerator system are operating is energy generation sustained and electricity produced. To date no attempt has been made to couple together an accelerator, beam target and nuclear reactor as a single system to produce a sustained nuclear chain reaction for greater than a nominal power output. A proposal for doing this at the Belgian nuclear research facility, StudeCentrum voor Kernenerge Centre d'etude de

* Corresponding author. Tel.: +44 1223 748575; fax: +44 1223 332662.
E-mail addresses: stevenjsteer@googlemail.com (S.J. Steer), macardin@nus.edu.sg (M.-A. Cardin), wjn21@cam.ac.uk (W.J. Nuttall), gtp10@cam.ac.uk (G.T. Parks).

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l'Energie Nucleaire (SCK·CEN), has recently received support from the Belgian government (SCK·CEN, 2010). The study is intended to be complete by the year 2024.

The financing of any nuclear power station is dominated by capital costs. There is therefore a significant financial risk associated with the construction of a nuclear power station. The risk is particularly large when demonstrating the first-of-a-kind of a technology; this issue is exemplified by the escalating costs and delays currently being experienced at the Finnish Olkiluoto facility (WNA, 2010), which is constructing the world's first European pressurised water reactor (EPR). It now appears as if the Finnish EPR will be a loss leader (Harding, 2007). It is not unheard of for first-of-a-kind nuclear reactors to be loss leaders; there have even been instances in the past where vendors planned from the outset to make their new design as such (Kaijser, 1992).

In addition to typical economic construction risks, ADSRs add unique new risks. These are due to the required accelerated proton beam and the beam target. Only the accelerator, and not the beam target, is the subject of the presented work. Contemporary accelerator systems are less powerful and less reliable than the specifications quoted for ADSRs (Burgazzi and Pierini, 2007; ENEA, 2001). Accelerator-specific R&D is being carried out to bridge this technological gap (Burgazzi and Pierini, 2007; Pierini et al., 2003; Teng, 2001). Even if R&D predictions are optimistic enough such that ADSRs do appear worth pursuing as a commercial proposition, there will still be risks associated with whether accelerator performance will meet the predictions.

With similarity to how unanticipated problems in the first-of-a-kind EPR have led to delays in its construction, an unexpectedly high rate of unplanned shutdowns of the first-of-a-kind ADSR accelerator system will affect its performance throughout its operational lifetime. If the reliability of a realised ADSR accelerator is poor then either the revenue of the ADSR will be low or the cost of failing to fulfil electricity contracts will be high. Regardless, the ADSR will return less marginal profit to offset the capital expenditure. This is not desirable for nuclear power stations as they typically operate as base-load electricity generators with low marginal costs of generation (Pouret et al., 2009).

In this paper an economic analysis of the benefits and costs associated with designing increased multiplicity for ADSR accelerators is deliberated. The aim is twofold. The first aim is to scrutinise formally an assumption that to the authors' knowledge has yet to be addressed in peer reviewed literature. The assumption is that designing an ADSR to have multiple LINear ACcelerators (LINACs) will untenably raise the cost of the ADSR. The analysis is mindful of, and therefore lends itself to, the possibility that types of accelerator other than LINACs might be the preferred choice for an ADSR; the cost of other accelerator types may be significantly less than LINACs and therefore the construction of multiple devices more reasonable.

The second aim is to recognise that, given the large capital that is at risk, a second accelerator will significantly reduce investment uncertainty, even though it will increase the cost of constructing the ADSR. This second aim is considered to be of particular interest for the first-of-a-kind ADSR. This is because, following R&D, this will be the time when there is greatest uncertainty regarding accelerator reliability. Treating the reactor vending and operating firms as a single company, it may be that a vendor–operator's strategy is to demonstrate the technology with a less risky ADSR driven by two accelerators. The long-term aim being that the nth-of-a-kind ADSR will be driven only by a single accelerator, should the technology prove to be successful.

The paper is structured as follows. In Section 2 there is a review of the demands on an accelerator used to drive a nuclear reactor. The performance achieved by contemporary high-power accelerators is detailed along with expectations of future performance from accelerator R&D literature. In Section 3 an ADSR designed with two accelerators is described whose primary aim is to reduce the reliability demands on the individual accelerators. A 4-step real options design framework is then used along with an economic model to assess the expected value of ADSRs designed with either one or two accelerators. In particular, the real options framework enables the recognition of an accelerator system design that is a balance between the one and two accelerator designs; this and a second flexible design that builds and tests an accelerator before constructing a reactor are discussed and also assessed in the economic model. In Section 4 a qualitative discussion is given, which highlights for all of the designs recognised pros and cons not captured by the presented economic analysis. At the end of the discussion a speculative design idea for a phased and integrated "park" of multiple reactors is suggested. The reactor park is motivated by the economic concerns of minimising both the levelised cost of electricity and the capital at risk. In Section 5 conclusions from the investigation are given. Appendix A explains possible methods by which dual accelerators might best be operated and Appendix B indicates the coinciding unplanned shutdown frequency of an accelerator network.

2. Technology review

2.1. Particle accelerators for nuclear reactors

The accelerator system of ADSRs is commonly foreseen to be either a single 3-stage LINAC (Pierini et al., 2003; Ruggiero, 1997) or a compact "circular" accelerating technology, for example cyclotrons ("warm" or superconducting), rapid cycling synchrotrons or fixed field alternating gradient accelerators. LINAC technology is the subject of the presented analysis. LINACs have been chosen because: (1) the beam power that they are expected to provide implies that the number of LINACs used to drive the ADSR will be lower than for the other technologies – this simplifies the presented analysis; (2) cost assessments have already been performed for ADSR LINACs; and (3) the planned Belgian SCK·CEN test reactor is intended to be driven by a LINAC (Pierini et al., 2003). Equivalent analysis of other technologies would be equally valid.

The analysis described assumes a single beam target ADSR design. Considering multiple targets would introduce additional complexity to the analysis, due to the requirement of a complex beam transport system for the multi-accelerator system considered in the presented analysis. For convenience and to frame the discussion such that it is clear that other accelerator types can be assessed in the same manner, 3-stage LINACs are referred to simply as "accelerators".

The ADSR accelerator system provides a high-energy, high-power proton beam, which impinges on a heavy metal beam target. This induces nuclear spallation reactions. Spallation is the act of splitting nuclei, creating a "cocktail" of species of smaller secondary nuclei. Among many other products, this generates a number of neutrons. The target is placed inside the reactor core. The neutrons induce additional nuclear fission reactions inside the core. These extra fissions sustain the fission chain reaction and thus energy generation, which promptly ceases if the accelerator system is turned off. Fig. 1 shows a concept diagram for the linear accelerator ADSR design.

An identified expectation of a commercially viable ADSR is that the accelerator system should not suffer more than approximately 5–10 unscheduled interruptions per year (of duration $\geq$1 s) or else the associated incurred costs of the unplanned shut downs will have unacceptable financial implications (ENEA, 2001). From a technical perspective, following detailed analysis it has been shown that the reactor core (not the accelerator system) of the planned