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Hedging Against Technology Risks of the Accelerator System of a First-of-a-Kind Accelerator-Driven Subcritical Reactor

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Abstract

Demonstrating the generation of electricity with Accelerator-Driven Subcritical Reactor (ADSR) technology will incur substantial financial risk both from traditional reactor construction uncertainties and new technology uncertainties such as the reliability of the accelerator system. The sensitivity of the economic value of ADSRs to the reliability of the accelerator system is assessed. The economic assessment considers an ADSR with either one or two linear accelerators driving it. The extent to which a second accelerator improves reliability is determined, as are the costs for that improvement. Two Real Options derived flexible designs for the accelerator system are also considered. In one a single accelerator ADSR can be expanded to having two accelerators, in the other an accelerator is constructed and tested before the reactor is constructed. Finally, a phased multiple-reactor park with a single system of multiple integrated accelerators is suggested and discussed.

Keywords nuclear power, particle accelerator, reliability, economic value

JEL Classification D81

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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. This reactor design is the Accelerator-Driven Subcritical Reactor (ADSR), the concept for which dates back to the 1990's (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

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Research and Development (R&D) programmes (European Technical Working Group on ADS (ETWG-ADS), 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 extreme to the point 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 l'Energie Nucleaire (SCK·CEN), has recently received support from the Belgian government (StudeCentrum voor kernenerge Centre d'etude de l'Energie Nucleaire, 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 (World Nuclear Association (WNA), 2010), which is constructing the world's first European Pressurised water Reactor (EPR). It now appears as if the 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 (ETWG-ADS, 2001; Burgazzi and Pierini, 2007). Accelerator-specific R&D is being carried out to bridge this technological gap (Teng, 2001; Pierini et al., 2003; Burgazzi and Pierini, 2007). 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 design flaws 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).

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 companies 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 n^{th}-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. First, there is a review of what the demands are 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. Next 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 or 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. A qualitative discussion is given, which highlights for all of the designs the pros and cons not captured by the current economic analysis. At the end of the discussion a speculative design idea for a phased and integrated "park" of multiple reactors is suggested. The design suggestions that feature in the reactor park are motivated by the economic concerns of making the levelised cost of electricity as low as possible, while also keeping the capital at risk to a minimum. Conclusions from the investigation are given at the end of the paper. Appendix A explains possible methods for how dual accelerators might best be operated and Appendix B indicates the coinciding unplanned shutdown frequency of an accelerator network.

Technology Review – Particle Accelerators for Nuclear Reactors

The accelerator system of ADSRs is commonly foreseen to be either a single 3-stage LINAC (Ruggiero, 1997; Pierini et al., 2003) 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) because cost assessments have already been performed for ADSR LINACs; and (3) because 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 generated 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. Figure 1 shows a concept diagram for the linear accelerator ADSR design.

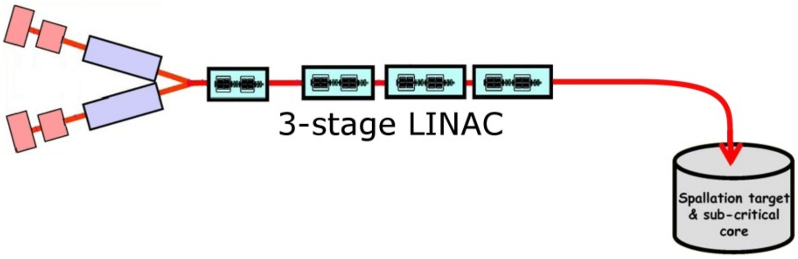

Figure 1: Concept diagram for a linear accelerator system ADSR. This diagram has been modified from reference (Pierini, 2007).

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 ≥ 1 second) or else the associated incurred costs of the unplanned shutdowns will have unacceptable financial implications (ETWG-ADS, 2001). From a technical perspective, following detailed analysis it has been shown that the reactor core (not the accelerator system) of the planned SCK·CEN test reactor would have to experience hundreds of sudden unplanned shutdowns per year before its structural integrity would be compromised (Nuclear Energy Agency (NEA), 2009). The planned SCK·CEN test reactor, however, is far from commercial scale; it is not necessarily a fair comparison with a larger reactor. In a recent presentation reviewing current knowledge on the number of unplanned accelerator shutdowns ADSRs can tolerate it has been stated that:

> *"Influence for the thermal shock damage on the ADS reactor system caused by beam trips has not been evaluated sufficiently...*
>
> *"...The acceptable frequency of beam trips ranges from 50 to 2×10^4 times per year, depending on the beam trip duration."* (Takei et al., 2010)

This statement was made in reference to a specific ADSR design of power 800 MW_{th}; the numbers are clearly subject to change. "Trip" is a common way of referring to an unplanned accelerator shutdown; this terminology is used henceforth.

The term Operational Availability (OA) is defined in this work to be the percentage of the year a subcomponent of the power station is *not* undergoing scheduled maintenance, it is therefore inclusive of the time down due to unscheduled shutdowns[i]. A high level view of the ADSR is taken, identifying two essential subcomponents: the accelerator system and the nuclear reactor (the reactor is considered to include all other key systems such as the beam target and window[ii]). The OA of the whole plant is given by the overlap in time that the subcomponents are operationally available. Because nuclear power stations are base-load generators it is expected that the power station will be contracted to sell electricity at all times when it is operationally available. The Capacity Factor (CF)[iii] is therefore the OA multiplied by its coefficient of reliability. For contemporary nuclear power stations (they do not require an accelerator) OA is approximately equal to the CF because they are highly reliable. A typical CF for a contemporary reactor is 75-90% (WNA, 2009).

Contemporary high-power accelerator systems at research facilities are 70% reliable when they first start operating. This rises to 90% for seasoned facilities (Galambos et al., 2008)[iv]. This takes about 5 years (Kim and Galambos, 2010). Seasoned facilities expect of the order of 7500 shutdowns per year (at OA = 70%) of duration ≥ 1 second (Galambos et al., 2008). These research

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[i] In this paper unscheduled shutdowns of accelerators are considered to occur when there is an accelerator beam interruption that lasts for > 1 second.

[ii] The proton beam exits the vacuum of the accelerator transport system through a thin "window" (typically a titanium-vanadium alloy) and impinges on the beam target (expected to be lead or lead-bismuth) where neutrons and other products are generated through spallation reactions. The radiation damage to the window and target will potentially cause them to have poor reliability characteristics.

[iii] Capacity Factor (CF) is the ratio of the actual plant power output to the output had it operated continuously at full power during the same period.

[iv] Within the reference reliability is termed "availability". "Availability" should not be confused with "operational availability", as defined in this paper.

facilities, however, work to budgets that do not allow for the maximisation of reliability that could be achieved with existing technology. Discussion with accelerator operators (Findlay, 2009) and examination of accelerator reliability optimisation studies (Pierini et al., 2003) suggest that if greater finance were available for: (1) adding additional components into existing accelerators; (2) having more spare parts available on site; and (3) hiring additional staff, then the rate of occurrence of trips is expected to significantly reduce. Importantly accelerator shutdowns of duration ≥ 24 hours could be almost entirely eliminated, as they are predominantly caused by insufficient staff numbers or spare parts not being immediately available (Findlay, 2009).

A study, *Preliminary Design Studies for eXperimental Accelerator-Driven Systems* (PDS-XADS), has examined how best to design a LINAC for ADSRs (Pierini et al., 2003). The study presents a favoured selection and configuration of components having taken into consideration that:

> *"In existing accelerator facilities it is common to schedule short and frequent (weekly) maintenance periods, whereas for the XADS [their ADSR design] clearly the maintenance policy needs to be compatible with the fuel cycle, requiring a more careful planning of fault tolerance and redundancies, or finding strategies in order to access devices that may fail frequently, without requiring the accelerator shut down."*

In consideration of this, it is preferable for the accelerator to be available or undergoing planned maintenance in concordance with the reactor; therefore it is most desirable for the OA of an accelerator, OA_{accel}, to be equal to the OA of its counterpart nuclear reactor, $OA_{reactor}$. It may, however, have to be less than this value, should poor reliability result in additional maintenance time improving the economic value of the ADSR (through the avoidance of costs associated with unplanned shutdowns). In this work $OA_{reactor}$ is a constant and has been assumed to be equivalent to expectations of Generation III power stations, which are predicted to have a CF of 85% ($OA_{reactor}$ for the ADSR is therefore 85%) (ETWG-ADS, 2001; Massachusetts Institute of Technology (MIT), 2003; University of Chicago, 2004; Kennedy, 2007). For an ADSR this corresponds to $OA_{reactor} = 85\%$. The presented calculations have been performed for OA_{accel} values from 40% to up to 90%.

It may be challenging to meet the accelerator reliability expectations of (Pierini et al., 2003); active researchers in the field of high-power particle accelerators have more conservative opinions regarding what accelerator technology is capable of achieving:

> *"From readily available data (Galambos et al., 2008) on high-power proton accelerators, and from the ~70% of the year for which these accelerators are typically scheduled to operate – maintenance being carried out when the machines are not operational, it is possible that a reliability of ~95% could be achieved by devoting ~50% of the year to maintenance, thereby restricting operations [OA_{accel}] to ~50% of the year."* (Findlay, 2009)

This statement implies that in order to reach high reliability (and therefore reduce the number of unplanned shutdowns during scheduled operation) the OA of a single accelerator ADSR will not be able to exceed 50%. The statement was made with the assumption that the accelerator receives regular (weekly) maintenance, in line with current practice, not in line with reactor fuel cycle schedules. It therefore implies that the accelerator and reactor OAs will not be harmonised.

As the ADSR will only generate electricity (and therefore revenue) when both the reactor core and an accelerator are operating, the realised ADSR CF is proportional to the degree of harmonisation of the reactor and accelerator maintenance schedules. Current practice for operating existing reactors is to extend fuel cycles for as long as possible, as this increases facility CFs (and hence revenue). At research-based accelerator facilities many regular maintenance shutdowns are needed to maximise reliability and beam quality; typically accelerators do not continually run for more than a few weeks at a time. The current maintenance practices for operating accelerators and reactors therefore do not lend themselves to synchronisation. This was considered during the design of the 3-stage LINAC developed in the European PDS-XADS (Pierini et al., 2003) – see quote above. They have designed an accelerator that is intended to operate for long periods between scheduled maintenance.

▪ Technology Review – Accelerator Reliability and ADSR Value Maximisation

The rate of occurrence of trips increases as the scheduled OA increases, i.e. the devices become less reliable as time for beam studies and equipment diagnostics is reduced. Contemporary accelerators experience over two orders of magnitude more trips than an ADSR can tolerate. Unless a full-scale test accelerator is constructed (see section "Step 3: Flexibility in Design") in advance of realising the first-of-a-kind ADSR, there is likely to be significant uncertainty regarding the trip frequency at any given OA of the accelerator. There will also be uncertainty in the relationship between trip frequency and different OAs.

The duration of shutdowns of contemporary accelerators ranges from microseconds up to months. The frequency at which shutdowns of a given duration or longer occur approximately follows a −2/3 power law, where shorter durations are more common than longer, see Galambos et al. (2008) and Steer et al. (2009). At existing accelerator facilities, shutdown durations ≥ 24 hours are typically due to insufficient numbers of staff and the lack of onsite replacement parts. These issues can be solved by making available additional finances. It is therefore assumed that these two factors will not be an issue for an operator of a commercial power station. It has been assumed that trips in contemporary research facility accelerators that would extend beyond 24 hours are fixed in exactly 24 hours. It is also assumed in all of the presented analysis that all reactor core shutdowns cause a closure of the plant 24 hours in duration, even if the accelerator trip duration is significantly shorter than 24 hours. This assumption has been made on the basis that nuclear regulator approved restart procedures will have to be enacted, and that these will take a considerable number of hours to carry out. If it should turn out that no such procedures are required then the average opportunity cost of an accelerator trip will reduce, allowing for more to be tolerated from an economic perspective.

In liberalised commercial energy markets there will be a financial cost associated with each instance that accelerator trips result in the unplanned shutdown of the ADSR. An assessment of that cost has been made by Steer et al. (2009). The assessment suggests that if an ADSR were to operate in the contemporary UK electricity market, then for each unanticipated 24 hour shutdown an ADSR experiences it will require ~0.43 days of successful operation to balance the cost incurred (i.e. excluding capital costs, it only becomes profitable to operate the ADSR if it is successfully operating for greater than 3 of every 10 days of scheduled operation). For $OA_{reactor}$ = 85%, this implies that it is not desirable for an ADSR to experience more than 365 days × 0.85 × (1 – 3/10) ≈ 200 shutdowns per year (each of duration 24 hours), or else it would be more economically attractive to close the plant.

Because the trip rate for a chosen OA_{accel} value and also the relationship between that trip rate and the rate for other values of OA_{accel} are not known, it is not possible to identify explicitly whether the financially optimal method of generating energy from ADSRs is to schedule the facility to run for a large fraction of the year, but with poor reliability, or for a smaller fraction of the year, but with increased reliability. The opportunity cost of each type of down time is not equal; while no revenue is made during planned maintenance, revenue is exceeded by the cost of failing to fulfil contracts during unplanned shutdowns, making it more expensive per unit time. For the topics discussed it is of no consequence which method is more valuable. One can theorise an equivalent device, which is 100% reliable and operates for a fraction of the year ranging from 0% to 85%. In these terms, the uncertainty regarding accelerator reliability can be comprehensively described by an effective $\underline{OA_{accel}}$ (where the *effective* OA assumes 100% reliability during scheduled operation). Assuming all other systems (e.g. beam target, heat exchangers, etc.) are 100% reliable, the *effective* OA_{accel} uncertainty solely dictates plant CF variances, which directly affect the quantity of electricity sales and hence the financial value of the device.

The hypothesis that there is potentially value in operating an ADSR with multiple accelerators, rather than only one is examined. The paper considers an ADSR driven by two accelerators; however, there is no reason why three, four or more cannot be considered. Each additional accelerator incurs an increase in the capital cost of the ADSR and will also increase the running costs of the facility. In exchange for these costs, additional accelerators reduce the reliability demands on the devices. It is therefore expected that there will be less uncertainty regarding the levelised cost of an ADSR driven by two accelerators, while also the net effect may be to improve their profit/loss margin.

The presented analysis has been performed using the assumption that an ADSR operator expects that the n^{th}-of-a-kind reactor should be able to sell electricity profitably with only one accelerator, but that for the first-of-a-kind ADSR a second accelerator may be required in order to limit the risks associated with testing the new technology.

In Appendix A potential modes of operation for driving a nuclear core with two accelerators are described. An economic evaluation of the ADSR value is not sensitive to which mode of operation is selected: it is a technical decision. Of concern to the economic analysis is that it is (conservatively) expected that both accelerators will be consuming power at all times of scheduled operation, and also that the reactor core will only suffer an unplanned shutdown at times when both accelerators trip in coincidence for an overlap period of at least 1 second in duration. As it is considered that both accelerators are consuming power at all times during scheduled operation, in the presented analysis a two accelerator ADSR has less electricity available to sell into the market than a one accelerator ADSR.

Analysis has been performed, identifying the expected frequency of coincident shutdowns of two accelerators over a period of 12 months for OA_{accel} = 85%. It assumes that trips in each accelerator occur completely independently of one another. Each unplanned accelerator shutdown results in a 24 hour shutdown of the ADSR; the maximum possible number of shutdowns is therefore 365 × 0.85 = 310 per year. For the remaining days of the year the reactor is down for scheduled maintenance. The analysis has been performed for a wide range of values of the total number of trips per accelerator per year. The duration of each of the trips is set such that it is in the range 1 second to 24 hours, distributed according to the −2/3 power law described in Steer et al. (2009) and references therein. The result of the analysis is presented in the spectrum in Figure 2.

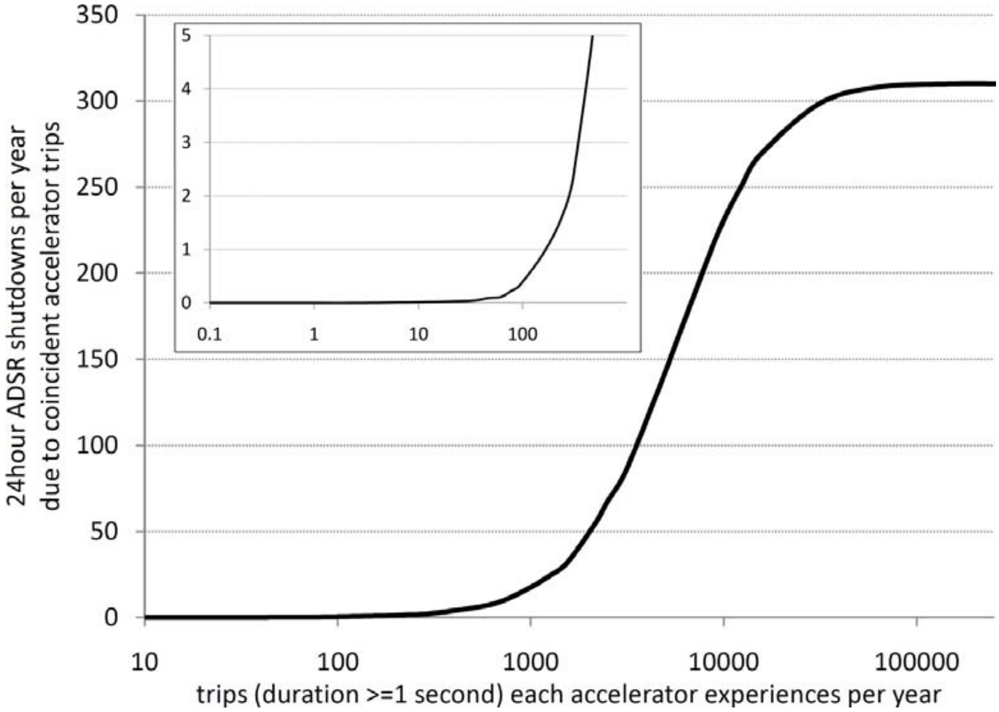

Figure 2: Annual number of coincident accelerator trips of duration ≥ 1 second for two accelerators for OA_{accel} = 85%. Coinciding trips cause a 24 hour shutdown of the ADSR. Inset is the same data for a different range. A single contemporary seasoned accelerator at a research facility is expected to experience ~7500 trips per year, while operating for only OA_{accel} ≈ 70%.

The spectrum in Figure 2 indicates that if two accelerator systems with power outputs that meet the requirements of an ADSR, but with contemporary reliability profiles (but operating at $OA_{accel} = 85\%$), were used to drive the nuclear core then it is expected that the reactor would be down due to unplanned shutdowns for approximately 185 days per year of scheduled operation. The spectrum also shows that at the limit where it starts becoming more profitable to sell electricity than not (~200 one day in duration shutdowns per year), each accelerator would be experiencing approximately 9000 trips of duration ≥ 1 second per year.

For a reactor driven by one accelerator (given the assumption of shutdowns lasting 24 hours), it is only sensible to discuss accelerators that trip less than ~200 times per year, or else the plant will be operating at a marginal loss and it is more financially beneficial not to sell electricity at all. In this reliability regime, a reactor driven by two accelerators experiences an average of less than 1 unplanned shutdown per year, as shown in the inset spectrum in Figure 2. Therefore, for comparisons between one and two accelerator-driven reactors, regardless of the effective OA_{accel} each accelerator can reach, a two accelerator configuration is approximately 100% reliable and can be scheduled to sell electricity for $OA_{accel} = 85\%$. This is reflected in the economic analysis.

Real Options Design Evaluation Under Uncertainty

A financial model for an ADSR has been developed to investigate the hypothesis that there is potentially value in having two accelerators, rather than one. To examine the hypothesis, the four-step real options process described in Babajide et al. (2009) has been used. In the first stage an economic model is developed to identify a deterministic value for a design (or in this case the two designs, named: "Single" and "Dual", in reference to the number of accelerators that drive the reactor). In the second stage the most significant uncertainties are taken into consideration, and the sensitivity of the designs to these uncertainties is identified. The third stage of the evaluation involves the identification of potentially valuable sources of flexibility in the design and also the relevant design considerations that need to be made in order to enable that flexibility. The flexible design is then compared to the deterministic accelerator configurations in the economic model, including the uncertainty. In the fourth step decision analysis methodology is used to recommend the most valuable deployment strategy between the considered designs.

Two parameters outputted from the economic analysis are used to identify the value of the different designs. These are the Levelised Cost of Electricity (LCOE) measured in units of £ /MWh and the required Capital Expenditure Before First Revenue ($CapEx_{BFR}$). The LCOE is directly comparable with the price of electricity and therefore is a measure of the profitability and competitiveness of the design. The $CapEx_{BFR}$ identifies the finance placed at risk during construction.

Step 1: Basic Economic Analysis

To contextualise the identification of the value of Single and Dual accelerator systems in ADSRs, all costs associated with an ADSR facility have been considered using a top-down approach, from the beginning of the pre-development process until plant closure, including setting aside funds for geological disposal of nuclear waste and decommissioning.

The work by Kennedy (2007) on Generation III nuclear power stations forms the central basis for the cost model. This work has been selected as the values used in the analysis are a compilation of multiple other economic assessments of Generation III nuclear power stations. The capital expenditure for construction is assumed to be distributed through time in the same shape as 0° to 180° of a sine curve; this is in the same manner as in the report: *The Future of Nuclear Power* (MIT, 2003). The interest accumulated on the construction loan (commonly referred to as Interest During Construction (IDC)) is calculated by the method described in the report: *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems* (Generation IV International Forum, 2007). The sum of the pre-development construction costs and their associated IDC identifies the total $\text{CapEx}_{\text{BFR}}$ at the time the plant comes online. The inputs to the ADSR model are given in Table 1. Except where explicitly stated otherwise in the table, inputs are taken directly from the work by Kennedy (2007). All costs are in 2006 money.

Table 1: List of parameters used in the financial model. Except where explicitly stated otherwise, the assumptions are taken from (Kennedy, 2007).

Parameter	**Assumption**	**Source/Comment**
Declared Net Capacity (DNC) of a single accelerator ADSR	600 MWe	This is a commonly cited size for a demonstrator ADSR. Physics and engineering considerations have driven the decision. The energy requirement of one accelerator (20 MWe) is considered to already be subtracted from the value.
Additional energy consumed by second accelerator	20 MWe	When operating two accelerators, the plant DNC is reduced by this value. The value is taken from common quotes for accelerator energy consumption. This is considered to be the upper limit for the requirements of an accelerator and the redundant accelerator may not require all of this energy, see Appendix A.
Pre-development costs	£250 million	Pre-development costs (e.g. site licensing) are assumed to be insensitive to plant size and type. Therefore the Kennedy (2007) EPR cost has been used.

Construction period of reactor and any accelerators constructed in parallel	6 years	In the “flexible” designs, see text, construction is (optionally) phased. There is only one construction phase for the Single and Dual designs.
Construction period for the additional accelerator in the “Expandable” design, see text	2 years to make the decision about whether to build it + 3 years construction time following the decision	Construction time has arbitrarily been halved to account for: foundations having been laid; the cryogenics facility only needing expanding and workers having had experience of constructing the first accelerator. This parameter is only used for the “Expandable” design, see text.
Construction cost of power station excluding the accelerator proper and cryogenics facility	£1625 /kWe (£975 million) + IDC (£274 million)	Based on Kennedy (2007) “Central” scenario for a first-of-a-kind, but increased as described in (NEA, 2000) page 32, using a scale factor of *n* = 0.425. This is assumed to include the accelerator’s civil works, site engineering and indirect costs.
Construction cost of a 1 GeV 10 mA (LINAC) accelerator and cryogenics facility	£290 million + IDC (£82 million)	Estimate from the XADS proposal (Safa et al., 2002) with a linear cost escalation of the “high-energy section” (excluding the cryogenics facility) to increase the 600 MeV beam energy to 1 GeV. A €1 = £1 exchange rate was used. Escalating from 2002 to 2006 money and cost savings made by purchasing multiple accelerators have been neglected.
Operational lifetime of reactor	40 years	
Operational lifetime of a LINAC	40 years	Assumed to be equal to the reactor lifetime. High-power accelerators do operate for these time scales. For example the Swiss PSI cyclotron is still in operation after 36 years.
Operation and Maintenance (O&M) cost of nuclear reactor	£7.70 /MWh	
O&M of an accelerator	£34 million per annum for a single accelerator, a £17 million per year increase for running two.	Based on reported annual running costs of the Spallation Neutron Source at Oak Ridge National Laboratory (Hickey, 2009) and the European Synchrotron Radiation Facility (ESRF, 2007; ESRF, 2008). Operating two accelerators in parallel assumes a 25% benefit of economies of scale.

OA of nuclear reactor	80% rising to 85% after the first 5 years	
OA of a linear accelerator	≤ 85%. The first 5 years of operation are 5% lower than the subsequent years.	When operating with only one accelerator this parameter is treated as an uncertain variable. No benefit is gained if it exceeds the maximum core OA (85%).
Fuel supply cost (thorium fuel)	£1.1 /MWh	Thorium does not require enrichment. A fast thorium reactor burns nuclear fuel more efficiently than a thermal uranium reactor. The Kennedy (2007) cost of uranium fuel has been modified to exclude enrichment costs (50%) and reduce the quantity of ore mined by a factor of 8 (Bryan, 2009). Mining costs per kilogram are assumed to be equal.
Combined radioactive waste disposal and decommissioning costs	£9 million per annum, savings grow at a real rate of 2.5% annually. This is a total of £583 million after 40 years of operation.	The Kennedy (2007) EPR geological disposal cost is the same (£276 million at closure) and the decommissioning cost is modified to £513 million /GW. This is a simple linear extrapolation to 600 MWe of the vendor cost quotes for 1600 MWe EPRs and 1200 MWe AP1000s. Fund payments are made at a fixed rate and therefore do not vary with sensitivity analysis on the *effective* OA_{accel}.
Contractual cost of unplanned shutdowns	£270,000 (mean loss made per 24 hour ADSR shutdown)	Taken from the analysis performed in (Steer et al., 2009) for the mean cost of a single 24 hour unplanned shutdown, using the contemporary electricity price.
Cost of capital	10%	Post tax real weighted average cost of capital

For a Single accelerator ADSR and for two different *effective* OA values (85% and 50%) of the accelerator a breakdown of the LCOE has been calculated, highlighting the expected cost structure of an ADSR. The LCOE is also given for the Dual accelerator ADSR. In the regime of reliability that allows one to consider a Single accelerator design at any OA_{accel}, the Dual accelerator configuration is always most beneficially operated at OA_{accel} = 85%. The cost breakdown is given in the stacked histograms in Figure 3.

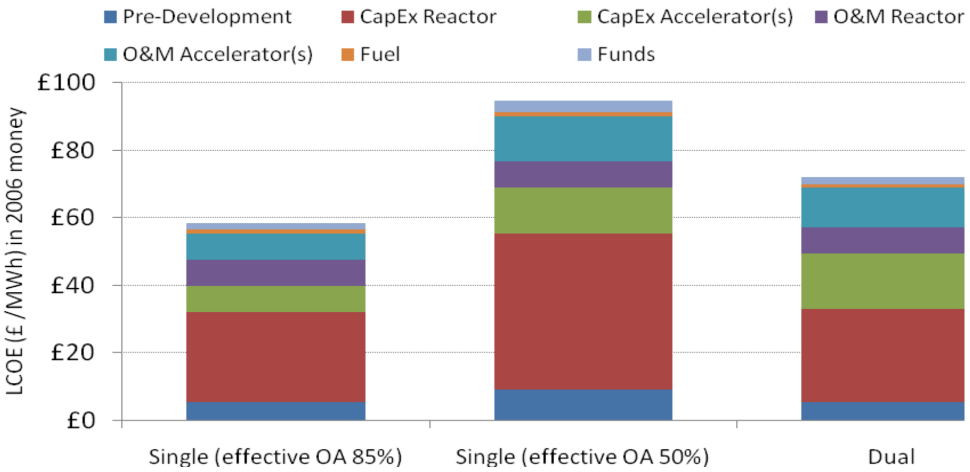

Figure 3: LCOE breakdown for the Single design at two different accelerator effective OA values and the Dual design, in the reliability regime where the Single design can be considered. In the figure "funds" refers to the money set aside for the combined geological disposal and decommissioning; and O&M stands for Operation and Maintenance.

- ### Step 2: Uncertainty

Development is taking place in improving accelerator reliability (Teng, 2001; Pierini et al., 2003; Burgazzi and Pierini, 2007; Pierini, 2007). It is, however possible that a realised first-of-a-kind ADSR will not meet its OA expectations. OA_{accel} is therefore treated as an uncertain variable in the economic model. By assuming that the reactor core and accelerator operate perfectly harmonious maintenance schedules, the LCOE per MWh for a Single accelerator ADSR has been plotted as a function of its *effective* OA_{accel}, see Figure 4. As described above, it is always most profitable to operate a Dual accelerator ADSR at $OA_{accel} = 85\%$. Its LCOE is therefore a constant in the presented analysis. The maximum OA value calculated is $OA_{accel} = 90\%$; this exceeds the maximum OA of the reactor, $OA_{reactor}$, which has been fixed at a value of $OA_{reactor} = 85\%$.

As the *effective* OA of the accelerator reduces, the LCOE rises rapidly for the Single accelerator design. The lowest LCOE in the sensitivity analysis is for the Single accelerator design at $OA_{accel} \geq 85\%$, and is equal to £58.59 /MWh. This is significantly larger than the contemporary price of wholesale electricity[v]. Even considering the potential for an increase in the future price of electricity, the presented analysis suggests that the first-of-a-kind ADSR might be a loss leader.

The spectrum in Figure 4 shows that the LCOE of a Single accelerator ADSR is sensitive to the *effective* OA achieved by the accelerator technology. For the plotted range the LCOE is roughly inversely proportional to *effective* OA_{accel}: halving *effective* OA_{accel} roughly doubles the LCOE. For Dual accelerators the LCOE is constant over the full *effective* OA range. The LCOE for the Dual accelerator configuration will measurably begin to escalate when the number of unplanned trips per accelerator reaches hundreds or more per year. (For context, in Figure 4 the Single accelerator ADSR at an *effective* $OA_{accel} = 40\%$ at maximum corresponds to a failure rate of ~ 95 trips per year.)

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[v] In 2009 the mean UK market index price of electricity was £34.08 /MWh (this value has been adjusted to 2006 money using the consumer price index).

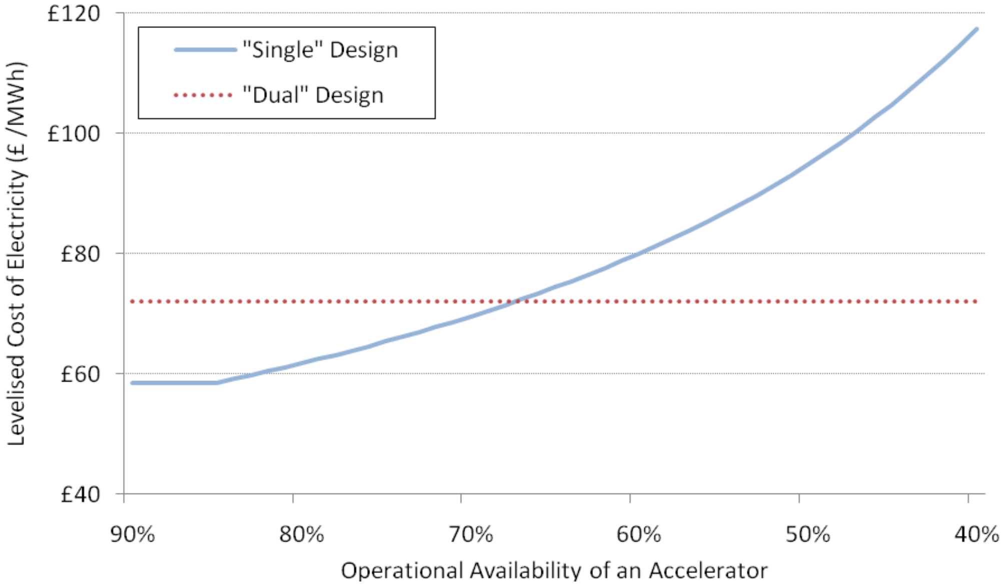

Figure 4: Levelised Cost of Electricity Production per MWh of electricity sold for a first-of-a-kind ADSR which has either a Single or Dual accelerator(s). Costs are in 2006 money.

The sensitivity analysis clearly shows that the outcome of the uncertainty regarding accelerator trip frequency for an ADSR will determine whether ADSRs are financially more valuable through one accelerator being constructed or through two. The capital expenditure commitment required by Single or Dual accelerator ADSRs is not captured by the LCOE analysis. A Dual accelerator ADSR requires a larger initial $\text{CapEx}_{\text{BFR}}$ (£2,493 million) than the Single (£2,121 million). The results presented in Figure 3 do not highlight all possible risks from other aspects of the realisation of an ADSR (construction delays, materials cost escalation, poor reliability of other key systems such as the beam target and/or window, skilled staff shortages, etc.). Although the Dual accelerator design reduces the technology demands on the accelerator system, it increases the financial exposure to risks from other aspects of the ADSR design by increasing the capital committed to the project.

Step 3: Flexibility in Design

It has been demonstrated that when constructing two accelerators rather than one, the operator hedges against the risk of numerous accelerator trips, but the Dual accelerator design is less valuable than the Single if *effective* OA_{accel} exceeds ~67%. The operator must also consider whether the increased certainty regarding the LCOE is worth the increased $\text{CapEx}_{\text{BFR}}$, which is subject to risks in construction and operation that are not considered in the presented work.

To try to capture the best aspects of both the Single and Dual accelerator configurations, a real options strategic decision making approach to building a *flexible* first-of-a-kind ADSR is considered; it has identified two more designs. This method of evaluation has previously proven to be successful in identifying the true potential value of projects as uncertainties are resolved. Real options enable this by allowing design-changing decisions to be made during the project (Myers, 1977; Dixit and Pindyck, 1994; Trigeorgis, 1996).

Typical discounted cash flow analysis assumes a full commitment to a project; it does not dynamically adjust decisions during the project (Dixit and Pindyck, 1994; Trigeorgis, 1996). By valuing a project through assuming that all decisions are made irreversibly at its beginning and not allowing for changes to be made as uncertainties are reduced, its maximum value may not be returned. With the Single and Dual accelerator systems in mind, one flexible design (named "Expandable") is considered by hypothesising that the ADSR operator initially constructs only one accelerator, but plans for the possibility of needing the second. By planning from the outset that a second accelerator might be constructed later, the cost of building the second accelerator, and thus switching design types from a Single to Dual accelerators, can be kept low (Silver and de Weck, 2007). For example, accelerator construction work that would require the ADSR to temporarily close and stop selling electricity in order to be carried out should be completed during the initial construction of the plant.

This Expandable design will incur $\text{CapEx}_{\text{BFR}}$ costs ensuring the site is suitable and configuring infrastructure such that it can easily accommodate an additional accelerator *if* it is desired. In Table 2 factors expected to be important in enabling the option to build a second accelerator are detailed. Cost predictions are only given for the factors that are expected to be financially significant. For calculations of the flexible design, the costs in Table 2 are paid for during the initial construction of the plant. If the second accelerator is constructed later, the model determines the cost of that accelerator to be the same as the cost identified in Table 1 subtracted by the costs already paid as given in Table 2. The cost of capital for building the second accelerator is assumed to be a real rate of 10%; this is the same as for the initial plant construction.

Table 2: Factors that will require attention during the initial construction of an ADSR, to ensure cost minimisation should a second accelerator be constructed during the ADSRs operation.

Factor	**Assumption**	**Source/Comment**
Digging the second accelerator tunnel	£35,000 /metre, 400 metres long (£15 million)	Cost per metre from reference (Ruggiero, 1997) assuming equivalent purchasing power parity and therefore an exchange rate of $1 = £1 and neglecting to escalate to 2006 money; value then divided by 2 to account for only carrying out essential work on the tunnel. Accelerator length calculated by extrapolating from (Giraud et al., 2004).
Enabling later expansion of the cryogenics facility	£5 million	This is one quarter of the total cost of the cryogenics facility (Safa et al., 2002).
Increased site size		The geographical site for the reactor must be able to accommodate two accelerators.
Planning site utilities		Ensure that there will not be any difficulties in later connecting the second accelerator to existing site utilities.

A second flexible design (named "Accelerator Test") is considered. In this design an accelerator is constructed (over 6 years) and then tested (for 2 years), based on the outcome of that testing the operator then decides whether to construct: a reactor; a reactor and a second accelerator; or nothing, thus abandoning the project. This design keeps the capital required to gain an understanding of accelerator reliability low (£442 million). However, the total $\mathrm{CapEx}_{\mathrm{BFR}}$ will be larger than for the inflexible designs as it is £2195 million for going on to construct a reactor or £2540 million for a reactor and a second accelerator.

The LCOE per MWh as a function of *effective* OA for the flexible Expandable and Accelerator Test designs are considered in comparison to the inflexible Single and Dual accelerator(s) designs, as seen in Figure 5. It shows that when comparing the Expandable design to the Single accelerator design, the cost of planning for the construction of a second accelerator has a negligible impact on the LCOE. The Expandable accelerator system is a good compromise between the risky, but potentially valuable, option of a Single accelerator ADSR and the more reliable Dual accelerator option, for which the most financially beneficial possible outcome LCOE is less good than the best arising from the Single accelerator design. The Accelerator Test design has a comparatively poor LCOE for all circumstances.

The sensitivity analysis in Figure 5 suggests that if an Expandable ADSR were constructed, in instances where $OA_{accel} < 68\%$ it becomes beneficial to build the second accelerator. Because financial discounting places more weight on revenue which is made sooner in a project rather than later, should the Expandable ADSR design have its second accelerator constructed, it can still have a considerably higher LCOE than the Dual design. This is due to the second accelerator not being available during the first five years of operation. Assuming the project is not abandoned, in the Accelerator Test design the second accelerator should be constructed along with the reactor when $OA_{accel} < 74\%$.

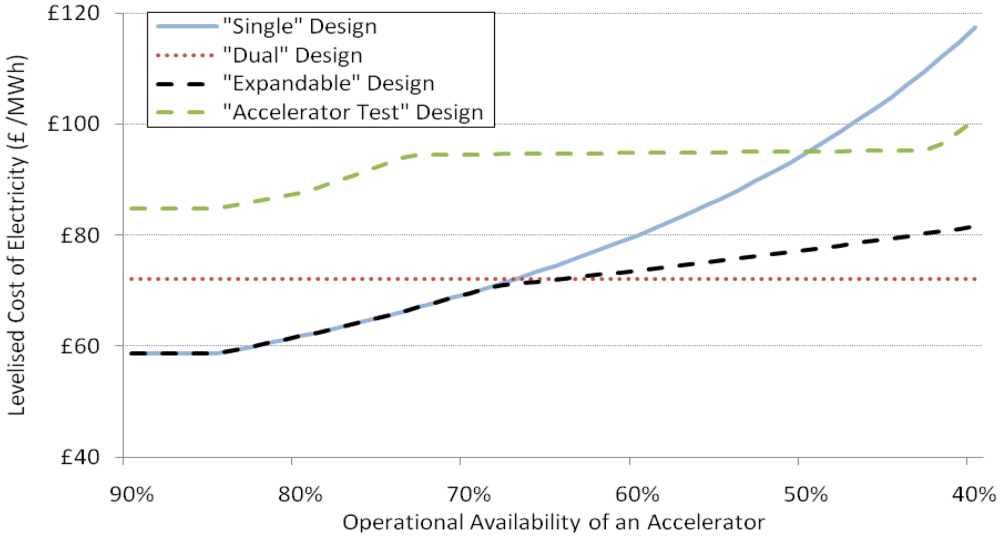

Figure 5: Levelised Cost of Electricity Production per MWh of electricity sold for two different flexible first-of-a-kind ADSRs compared to inflexible designs of one or two accelerator systems. Costs are in 2006 money.

Step 4: Selecting a Design

The sensitivity analyses showing the correlation between LCOE and the effective OA indicate which design has the lowest LCOE for a given accelerator performance. The challenge to a company planning on operating the first-of-a-kind ADSR is that it will not know the effective OA until after an accelerator has been constructed and operated for a number of years. To aid the managerial choice of which design to use, decision tree analysis is suggested. The decision tree approach assigns probabilities for the likelihood of occurrence of defined scenarios. From this information the expected value of the different designs is extracted, while remaining quickly tractable. Presently, three example scenarios have been hypothesised to demonstrate the decision tree approach. These scenarios indicate three different standards the accelerator technology might reach once realised (Optimistic, Central and Pessimistic). The scenarios are outlined in Table 3.

Before acquiring the site of the future plant a company must commit either to the Single, Dual, Expandable or Accelerator Test design. In the decision tree methodology the operator assigns probabilities of occurrence to the scenarios outlined in Table 3 (or to scenarios of its own choosing). In this example these probabilities are assigned to be: ρ_O, ρ_C and ρ_P for the Optimistic, Central and Pessimistic scenarios, respectively. These probabilities and the LCOE for each OA outcome enable the expected LCOE of each design approach to be calculated.

Table 3: Three possible outcomes for the effective OA of a realised Single accelerator ADSR.

Reliability Scenario	**Details**
Optimistic	The *effective* OA of an accelerator can match the reactor OA (85%). The system is ~100% reliable.
Central	Accelerator reliability is greatly improved compared to contemporary systems, but the *effective* OA is only 70%, which results in the plant capacity factor being slightly lower than other forms of nuclear power station.
Pessimistic	Reliability is poor. It may never be possible to construct accelerators reliable enough for ADSRs to return a profit. The *effective* OA of the accelerator system is 50%.

The branches of the decision tree in Figure 6 correspond to the combinations of technology scenarios (Optimistic, Central and Pessimistic) and design decisions (Single, Dual, Expandable and Accelerator Test). If one of the flexible designs is chosen then there are additional branches as a second decision must be made. In the case of the Dual accelerator design, the technology scenario does not impact on the LCOE, and so only one branch has been included. Because the LCOE is the metric of choice in this decision tree and not net profit/loss, project abandonment options have not been considered.

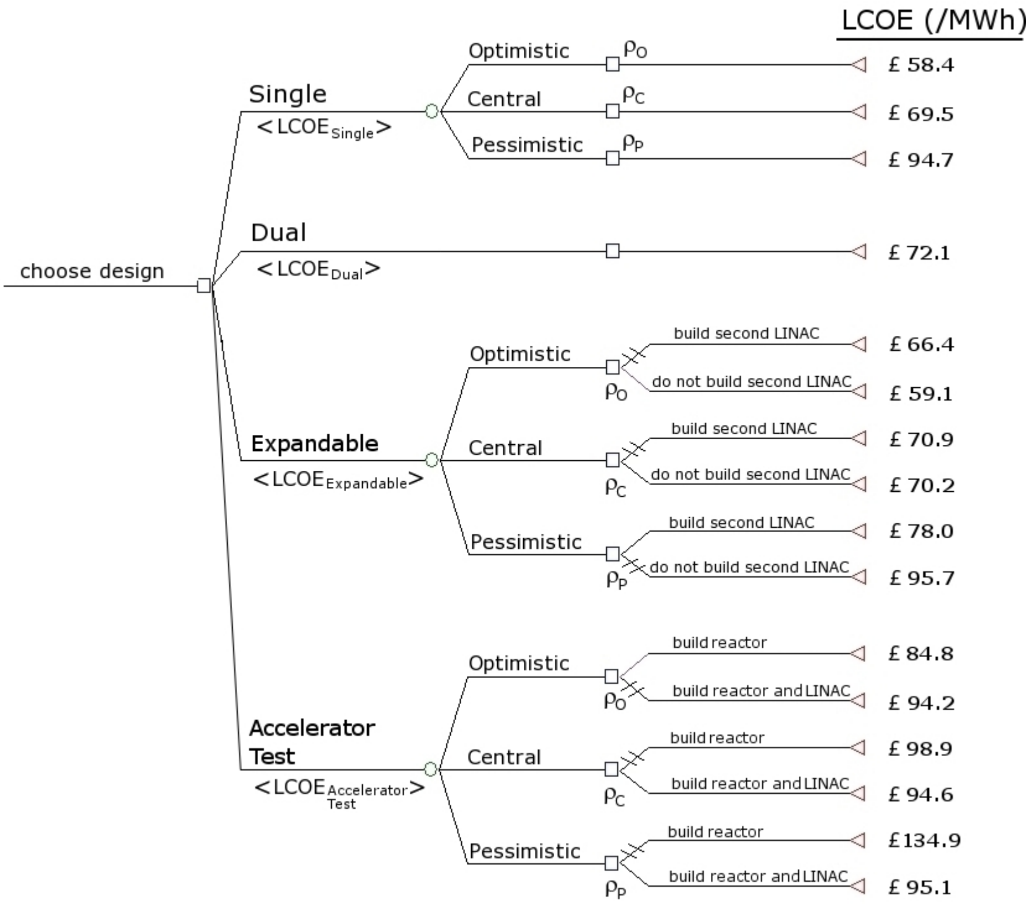

Figure 6: Decision tree for strategic decision making. The inflexible and flexible designs are considered. Three technology scenarios are presented as example outcomes (Optimistic, Central and Pessimistic). The LCOE per MWh (in 2006 money) for each design choice and realisation of the OA is indicated. Decision points are indicated with squares and uncertainty is resolved following chance nodes, which are the circles. Double slashes indicate a decision that it is not beneficial to follow.

The expected LCOE of each design is used to aid the decision of which to build. The expected value is determined by considering the value of each branch and its probabilistic likelihood of occurrence. For example, if ρ_O, ρ_C and ρ_P indicate the likelihood of realising each technology scenario and $LCOE_O$, $LCOE_C$ and $LCOE_P$ are the LCOE of the Optimistic, Central and Pessimistic scenarios, respectively, then the expected value of the Single accelerator configuration ($LCOE_{Single}$) is:

$$<LCOE_{Single}> = (\rho_O \times LCOE_O) + (\rho_C \times LCOE_C) + (\rho_P \times LCOE_P)$$

The design that returns the lowest expected LCOE will be the most valuable design, on average. The operator must still consider the up- and down-side risks. The accompanying paper by Cardin et al. (2010) gives more detail on this.

▪ Discussion

From a reference point of a “benchmark” Single accelerator ADSR, adding additional accelerators reduces reliability requirements on each individual accelerator, in exchange there is an additional capital expenditure and an increase in the facility running costs. This analysis has considered 3-stage LINAC accelerators. Their capital cost is large to the point where, if it is anticipated that the most valuable design for an ADSR is for it to have more than two LINACs, then ADSRs will probably never be competitive in liberalised electricity markets. Other types of accelerators that require less capital will continue to be cost competitive for higher multiplicities of the devices. However, establishing the most valuable design for the ADSR will only be possible by also considering other issues such as: the power provided per accelerator; its reliability; ease of operation; complexity of beam transport; accelerator-induced activation of work areas; and the increasing complexity of reliably switching between which accelerators are providing beam into the core as the number of accelerators and trips per accelerator increase.

From presently available data the relationship between the frequency of accelerator trips as a function of the fraction of the year an accelerator is scheduled to operate is not well defined. The best method of scheduling when the ADSR will sell electricity into the market is therefore unknown. At present, one cannot establish whether it is better to schedule sales for a small fraction of the year, with high reliability or to schedule sales for a large fraction of the year and then pay the cost of a comparatively large number of unplanned shutdowns. Not understanding the relationship also prevents direct comparisons between the performance of Single and Dual accelerator-driven reactors. It has only been possible to draw comparisons in the presented analysis because the Single accelerator ADSR can only feasibly operate at an accelerator trip frequency that is so low that the Dual accelerator ADSR is approximately perfectly reliable for the entire range of considered accelerator reliabilities. This will not necessarily continue to be the case if an analysis is performed between different designs that involve numerous cheaper low-power accelerators.

This analysis has assumed perfect harmonisation of reactor and accelerator maintenance schedules, but contemporary accelerator systems require frequent maintenance in order to ensure high beam quality, while nuclear reactor cores are preferably operated continuously for extended periods of time. If realised accelerators cannot reliably operate for extended periods without a break, for a Single accelerator ADSR it will not be possible to harmonise the accelerator maintenance schedule with the reactor schedule. A Dual accelerator system will be more tolerant of this, as the design permits the use of less reliable accelerators, i.e. it may be more valuable to postpone otherwise scheduled maintenance until the reactor is also scheduled to shut down.

If an ADSR is thorium fuelled there is a possibility that the reactor will achieve a higher OA compared to contemporary uranium thermal reactors. In uranium reactors there are two key factors that limit the fuel cycle, which is typically 18 months (WNA, 2006). One is the depletion of fissile material; the other is the increase in neutron-absorbing fission products. Each of these issues adversely affects the reactor neutron economy, which eventually requires the reactor to shut down for refuelling. Thorium fuel is a breeder of fissile nuclides. A thorium reactor will breed fissile material at a similar rate as it is burned (Carminati et al., 1993). In principle, it is only the build up of fission products that leads to the need to refuel a thorium fuelled reactor. This potentially extends the fuel cycle to many years. It may therefore be possible for a thorium reactor to reach $OA_{reactor}$ = 95%, which would involve its operating continuously for several years between planned shutdowns. The prolonged fuel cycle that one might anticipate from a thorium fuelled ADSR is expected to exacerbate the issues in harmonising maintenance schedules, as discussed in the previous paragraph.

When two accelerators are constructed, rather than one, they result in the same ADSR performance for an accelerator trip rate of many hundreds per year, rather than a few tens. It is therefore possible to reduce significantly the R&D that is required to build an ADSR, by making a Dual accelerator ADSR the goal design rather than the contingency design. Given this, a company may wish to concentrate on dual accelerators and reduce its need for R&D. Analysing the cost of developing improved accelerator reliability and how component cost correspondingly increases or decreases will indicate when it is most valuable to switch from research to plant construction.

It is anticipated that a construction cost saving would be made by simultaneously building two accelerators. The presented analysis has not taken this potential saving into account for the Dual accelerator design (and so one might expect the LCOE of the Dual design to be lower than the presented assessment). The saving is unlikely to be as great if the accelerators are built at different times, as is the case in the Expandable and Accelerator Test designs. Also for these designs a second construction phase is required that will also be subject to construction risks, such as project overrun or material cost escalation.

The key benefit of the Accelerator Test design is that if accelerator performance is determined to be too poor for ADSRs to be profitable a loss of only £442 million will be made by abandoning the project after the initial accelerator test. The loss made could be as much as four times as large for the Single accelerator design. The Dual and Expandable designs, however, are very tolerant of poor accelerator reliability. At closure the Dual design will also have returned a net loss of ~£442 million if the electricity price is £10 / MWh lower than its LCOE, unless accelerator performance is extremely poor.

A factor that only received limited attention in the presented analysis is the change in accelerator reliability as a function of time. In contemporary research facility accelerator systems it is typical for the reliability of the accelerator beam to increase from ~70% in the early years of operation to ~90% for a mature facility (Galambos et al., 2008). The presented analysis has assumed that the *effective* OA_{accel} increases by 5% after 5 years of operation of the accelerator. Should ADSR accelerator reliability improve with a steep learning curve, then the early years of operation of a Single accelerator ADSR would have a poor *effective* OA_{accel}. The LCOE would therefore be significantly increased, particularly in consideration of the effects of financial discounting.

A speculative idea for a “reactor park” is suggested aimed at improving the economic case for ADSRs. Aside from the traditional benefits of building multiple reactors at a single geographical site (e.g. sharing site utilities), a reactor park has potential for increasing the value of ADSRs through improved operation. If a single accelerator cannot reach high reliability, it has been shown that an ADSR has its value increased by building a second accelerator. However, the performance and cost of constructing two accelerators may be excessive. If multiple reactor cores are constructed at a single location then they may be able to share the accelerators between them, achieving optimal benefit through balancing accelerator cost and reliability.

For example, if three reactor cores are to be constructed, then a potentially valuable way of doing this would be to construct them at the same site along with 4 accelerators in a configuration where all of the accelerators can provide their beam to any one of the reactors at any moment through a carefully managed beam transport system, which is able to quickly respond to the failure of an accelerator. Only 3 of the 4 accelerators would need to be working at any given time in order to keep all 3 reactors generating electricity (Appendix B indicates the frequency at which failures in the accelerator network would lead to the shutdown of one of the three reactors). It may be most efficient to first construct only a single reactor and two accelerators, followed by twice building an additional reactor and accelerator in two subsequent phases. If, as discussed above, accelerator reliability is initially poor, but improves significantly over the first few years of operation, then this phasing would efficiently reduce the impact of the period of poor reliability for each new accelerator.

The principle of a reactor park which hosts an integrated network of accelerators also has benefits regarding the management of the maintenance schedules of reactors and accelerators, which are anticipated to be poorly harmonised when considering only a single reactor. Figure 7 shows a concept sketch of such a reactor park, with a suggestion for how to phase its construction.

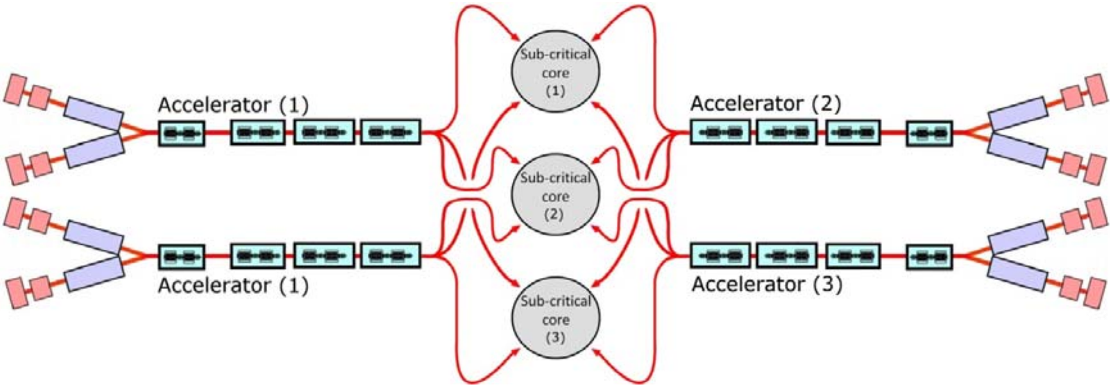

Figure 7: Concept diagram for the suggested reactor park with an integrated network of accelerators and reactor cores. The numbers in brackets indicate in which of the three construction phases the reactor or accelerator is constructed. This diagram has been modified from reference (Pierini, 2007).

▪ Conclusions

If an ADSR operator were to sell electricity into the contemporary UK electricity market, it would only return a marginal profit if it successfully delivered electricity for more than 3 days in every 10 of its contracts. By assuming that all other systems are 100% reliable and that an accelerator system failure will cause a shutdown 24 hours in duration, it is established that it is not worth scheduling to sell any ADSR-produced electricity unless the accelerator fails less than ~200 times per year.

Assuming that the relative frequency of failure durations of future accelerator systems express similar behaviour to that of contemporary ones, it has been demonstrated that an ADSR driven by two accelerators will shut down ≤ 200 times per year with accelerators that individually trip many hundreds to low thousands of times per year. The feasibility of the Dual accelerator design hinges on there being a system in place that enables one accelerator to compensate for the other within a second of it experiencing a fault.

A top-down financial cost-benefit-analysis has been performed for ADSRs. The financial model has been used to examine by how much a second accelerator escalates the cost of generating electricity with an ADSR. Without commenting on the future price of electricity it has been shown that if accelerator performance is poor, Dual accelerator ADSRs do become more valuable than Single accelerator designs. It has also been shown that Dual accelerator ADSRs eliminate nearly all of the investment uncertainty when considering only risks associated with accelerator performance. The downside of this is an increase in $\text{CapEx}_{\text{BFR}}$ of ~17.5%. Once other risk factors are taken into account, such as construction delays, the increase in initial capital at risk might be considered more important than increased reliability during operation.

Real options analysis has identified two more first-of-a-kind ADSR designs. One is an Expandable design, where initially a single accelerator is built and a second is planned for should it be required. The cost of planning to later build a second accelerator is expected to negligibly increase the LCOE if it is not constructed. The Expandable design does not increase significantly the $\text{CapEx}_{\text{BFR}}$. This design provides the option to improve reliability, should that be required. The most significant trade-off in the presented economic analysis is that reliability can only be improved after 5 years of reactor operation, which significantly increases the LCOE compared to the Dual design in outcomes where accelerator performance is poor. Qualitatively the issue has also been raised that building the accelerators at different points in time, rather than in parallel, may result in missing out on potentially large economies of scale savings.

The second flexible design is the Accelerator Test design. In this case the capital required to test accelerator performance is minimised through only constructing an accelerator at first and then building the reactor (and possibly a second accelerator) later if it is determined to be beneficial to do so. For this design the $\text{CapEx}_{\text{BFR}}$ and the LCOE are significantly worse than for all of the other designs in nearly all circumstances. The very high tolerance of poor accelerator reliability of the Dual and Expandable designs means that in effect they can also test accelerator performance for a similar investment cost as for the Accelerator Test design. This is because they (nearly) guarantee successful electricity sales after construction. In addition to testing the accelerator system these designs will also test all other facets of the design of an ADSR.

The concept of a reactor park has been suggested as a way of improving the economic case for generating electricity from an ADSR. The reactor park is expected to cope with accelerator trips in a more financially efficient way than is possible for a single reactor. Greater flexibility in the construction of accelerators and reactors is anticipated. In a follow-on from this study the real options technique and the decision analysis methodology have been applied with greater scope to the design suggestion of an ADSR reactor park (Cardin et al., 2010).

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Appendix A – Modes of Operation of a Dual Accelerator ADSR

Three modes in which an ADSR with two accelerators might most beneficially operate have been identified, they are labelled (A), (B) and (C). Details of the modes are given:

(A) Both accelerators provide 50% of the required proton flux. In the event that one accelerator experiences a trip: (1) the other must double its beam current and therefore the proton flux it is delivering within 1 second; (2) the ramping must not induce a trip in the remaining accelerator; and (3) all elements of beam transport must be able to adjust for the change in beam dynamics as the beam intensity is doubled, ensuring: (a) that the target receives 100% of its required proton flux; and (b) that there is insignificant irradiation of work areas.

(B) One accelerator provides 100% of the required proton flux until it experiences a trip, at which point the second accelerator takes over. It is assumed that the beam current is negligible or, for example, the ion source extraction high voltage supply is off, but all other elements of the second accelerator are always in operation. When the first accelerator trips, only the ion extraction high voltage supply needs to be turned on in order for the second accelerator to start providing protons to the beam target. The ADSR will now be driven by the second accelerator until it trips, at which point the first accelerator follows the same process and takes over.

(C) While one accelerator provides 100% of the required protons to the target, the other accelerator operates at full power with its protons directed into a beam dump. When the first accelerator trips the other has its beam redirected from the beam dump into the reactor.

Full analysis of these modes of accelerator redundancy has not yet been attempted. Notional advantages and disadvantages of each method are given. In all modes *each* accelerator is consuming equal to or nearly full power (100% or required protons). This cost will be the least for mode (A). Also, in this mode following an accelerator trip, the reactor core will still receive half of its required spallation neutrons. This will reduce the rate at which the fission reactions cease effectively extending the time window for doubling the beam current of the remaining accelerator. Handling the beam dynamics of this mode may be difficult. In modes (B) and (C) the beam dynamics will be less complex, as the accelerators only operate at a single current and don't ramp between two. Comparing modes (B) and (C), mode (C) is expected to be less demanding on accelerator reliability as it is considered more straightforward to adjust a magnetic field than ramp the high voltage supply; however, in this mode the beam dump will be subject to significant irradiation. It may be beneficial or even necessary to keep the redundant beam duty cycle very low in order to limit this irradiation. Swiftly increasing the duty cycle could be challenging. The redundant beam of mode (C) might be utilisable as a source of income. In mode (B) there is a risk of misdirecting the beam thus creating a hazard or damaging equipment.

In this mode it may be possible to only switch on systems other than the ion source high voltage as and when they are required, reducing accelerator power consumption.

The cited 1 second time window for switching on (or ramping) the second accelerator is in reference to a 80 MW_{th} fast reactor fuelled 20.5% by plutonium and 79.5% by natural uranium (D'Angelo and Gabrielli, 2003; D'Angelo et al., 2004). If the reactor fuel were to be switched to an alternative fuel (e.g. thorium) the change in the delayed neutron fraction of the fission reactions will increase or decrease the time window for meeting the proton flux deficit, therefore reducing or increasing the demands on the accelerator-switching mechanisms. This will affect all proposed modes of operation.

Appendix B – Frequency of Coinciding Unplanned Shutdowns of an Accelerator Network

An ADSR reactor park consisting of three reactors and four accelerators would be least reliable at times when all three reactors are scheduled to sell electricity. It is assumed that all four accelerators would be operationally available at these times. One of the three reactors would experience an unplanned shutdown if two of the four accelerators trip in coincidence. In the limit that all of the reactors are scheduled to sell electricity for the same 85% of the year the rate at which one of them would experience an unplanned shutdown due to trips in the accelerator network is given in the spectrum in Figure 8.

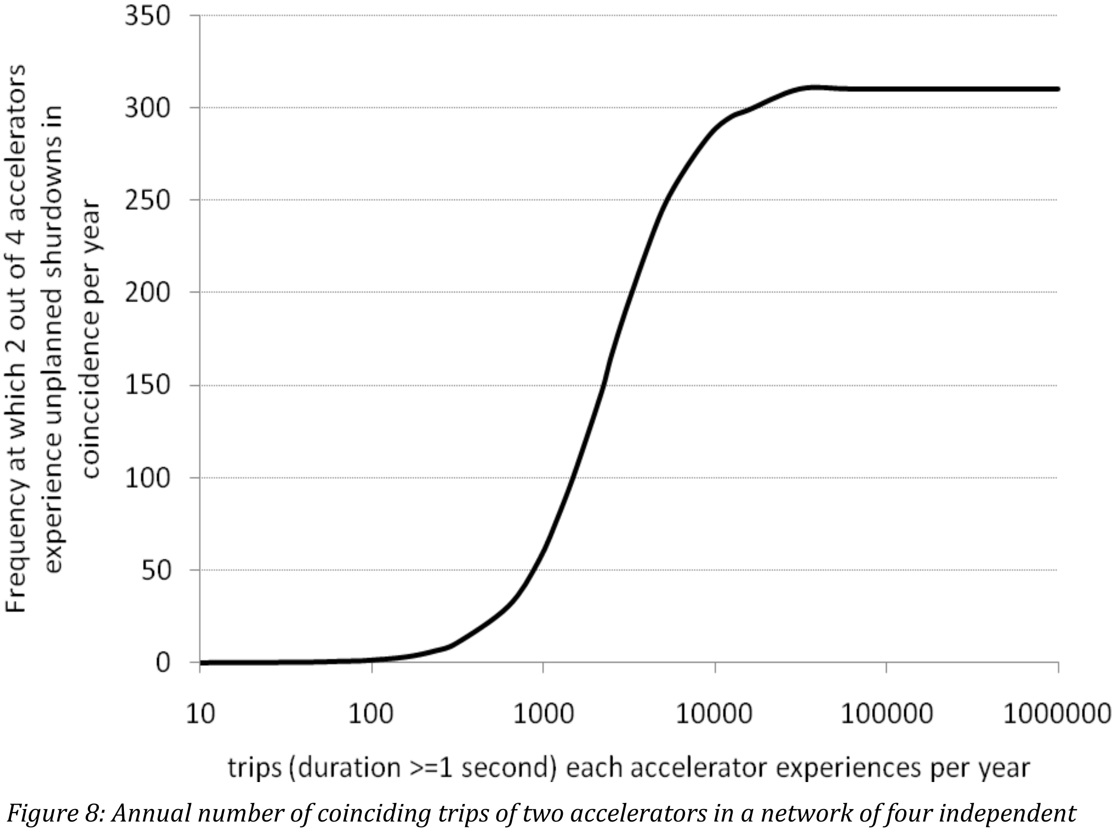

Figure 8: Annual number of coinciding trips of two accelerators in a network of four independent accelerators plotted as a function of the number of trips each accelerator experiences. This assumes that all of the accelerators are scheduled to operate for the same 85% of the year as each other.