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Accelerator-Driven Subcritical Reactor: "Straw-man" Design Concept Development

Thorium Energy Amplifier Association, Reactor Group Design Development Exercise: 21st May 2010

Foreword

The aim of the Thorium Energy Amplifier (ThorEA) Association is to aid and promote research and development (R&D) into Accelerator-Driven Subcritical Reactor (ADSR) technology, with the ultimate goal of seeing a commercial demonstrator reactor constructed and tested. To benefit the process of identifying the most desirable design concept for a commercial ADSR a small group of six members of ThorEA have carried out a discussion-based design exercise. The exercise was aimed at overcoming the sometimes overwhelming issue of there being strong a correlation between different ADSR design elements. The session used scenarios to develop potential ADSR designs. These designs are not concrete ThorEA ADSR recommendations; however, they are intended to be thought provoking. They indicate prominent design options for varying placements of ADSRs in world markets and highlight correlations in design elements.

Format of the discussion-based design exercise

The exercise was carried out over 2½ hours at the Engineering Design Centre of the University of Cambridge Engineering Department on the 21st May 2010. Six members of ThorEA were in attendance at the meeting, these were: A. Ahmad, D.J. Coates, L.V.N. Gonçalves, W.J. Nuttall, G.T. Parks and S.J. Steer. The primary aim of the decision making exercise was to identify a "straw-man" (outline/concept) for how an ADSR could best be designed.

The methods implemented during the exercise were inspired by the strategic roadmapping techniques of the University of Cambridge Institute for Manufacturing (IfM). Details of these techniques are available on their web site, see: http://www.ifm.eng.cam.ac.uk/ctm/trm/ *[Accessed 5th May 2010]*. Strategic roadmapping has previously been tailored and applied to suit ThorEA's needs during its own roadmapping session, which was carried out on the 7th and 8th September 2009 (A summary of this strategic roadmapping session is available on the ThorEA web site, see: http://www.thorea.org/publications/ThorEARoadmappingSummary.pdf *[Accessed 1st July 2010]*). Having gained experience in using the strategic roadmapping technique, the principles of efficiently eliciting information from a group of expert participants were used as a foundation for the straw-man decision-making exercise.

Session Preparation

Due to there being only 2½ hours available in which to carry out the exercise, it was imperative that careful preparations were made in advance of bringing the participants together. Prior to the session 9 different design elements were identified as being pivotal to defining the ADSR concept. There were:

- Fast or thermalised reactor
- k_{eff} value ~0.995 (~2 MW beam) or ~0.985 (~10 MW beam)
- LINAC or compact accelerator
- Single or multiple spallation targets
- Window or windowless target
- Fuel composition (multiple options)
- Open or closed fuel cycle
- Modular cores or a single large one
- Coolant choice (multiple options)

The challenge of identifying the best option for each of these design elements is twofold. First the benefits and challenges of the options within each design element must be clearly understood to allow the best one to be selected. Second, one must recognise the degree to which selecting one design element affects other decisions. For example, if the decision is made that the neutrons will not be moderated then that will prevent the use of water, for example, as a coolant as it will thermalise the neutrons.

In order to overcome both the issue of appreciating the challenges and benefits of each option within each design element and understanding the impact one decision has on other design elements the preparation addressed three areas: information gathering, identifying the interactions between design elements and design element decision-making.

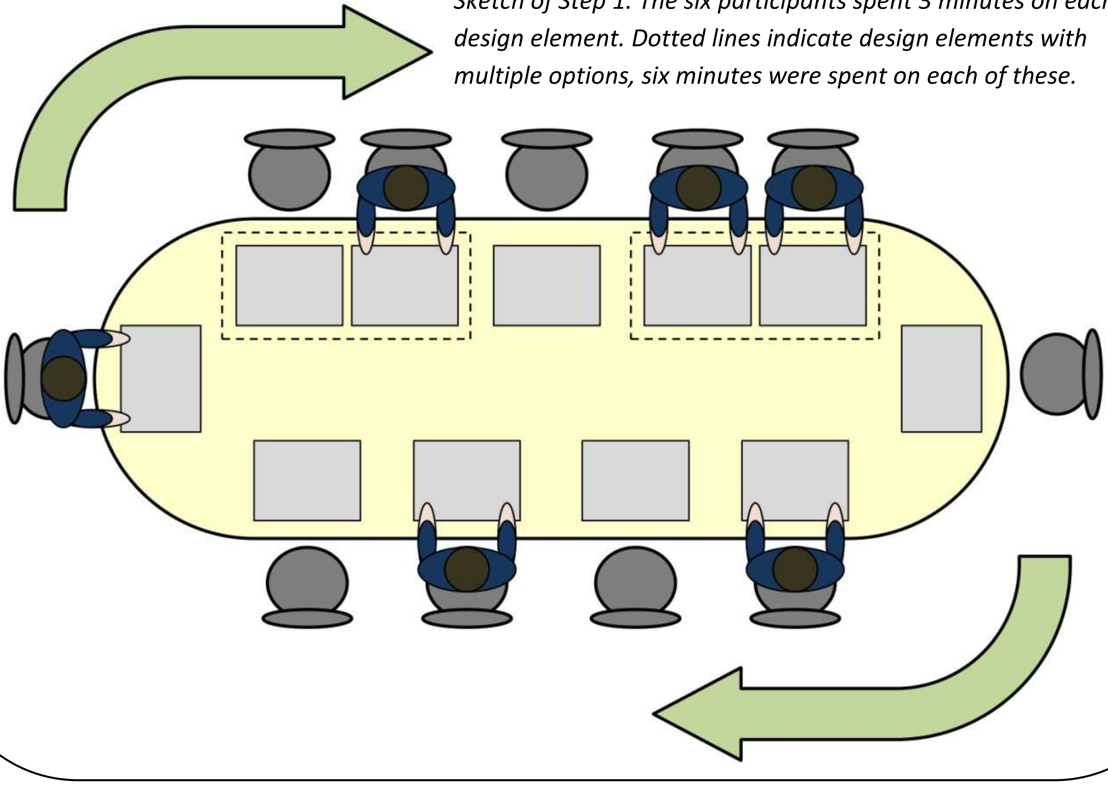
For information gathering sheets were created so that during the exercise participants could write down the pros and cons of each option, this formed Step 1 of the exercise.

Due to the complexity of the interactions between design elements a matrix was created before the exercise began. The matrix used a traffic light colour coding system to identify the extent to which each design element influenced the decision being made in another element. To save time this matrix was completed prior to the exercise. The matrix mediated the decision making exercise in Steps 2 and 3.

The preparatory work for Steps 2 and 3 was a single process. In these steps of the exercise specific decisions were made regarding the design of the ADSR. Outline sheets were created which listed the 9 key design elements. When a decision was made it was included on the sheet, therefore allowing the whole group to be clear on exactly what the status of each ADSR designs was.

Step 1 – Information Gathering

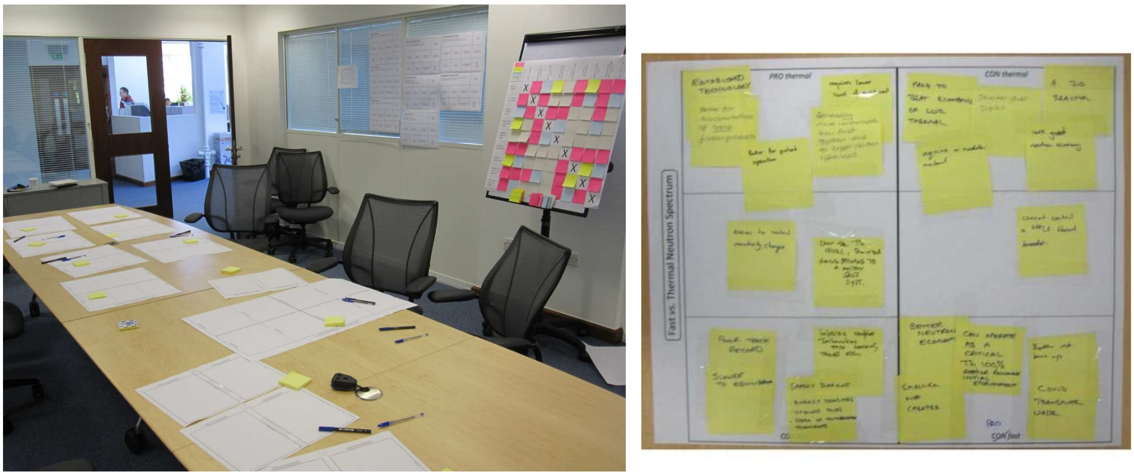
In order for design decisions to be made it was critical that the key pros and cons of each option were deliberated and that the information was disseminated to all of the group members. The information sheets created in the preparatory phase were used for this purpose. Each sheet was dedicated to one of the elements of the design and contained within it boxes for listing the pros and cons of each of the options available for the relevant design element. The sheets were laid out to form a loop about a large table. The participants were asked to sit down in front of one of the sheets (i.e. a design element) and spend 3 minutes writing down positive and negative features about the available design options. They then moved around the table in a clockwise direction, such that they each added information to all of the categories. Usually each design element consisted of two options; however, the fuel composition and coolant design elements have more. For these two categories the participants spent an additional 3 minutes listing pros and cons of the design options, to ensure that they were considered in sufficient detail.



Sketch of Step 1. The six participants spent 3 minutes on each design element. Dotted lines indicate design elements with multiple options, six minutes were spent on each of these.

The sheet for a typical design element with a dichotomous design choice was segmented into six cells. For the example of a thermal or fast reactor, four of the cells were: pros for thermal reactors, cons for thermal reactors, pros for fast reactors and cons for fast reactors. The remaining two were pro thermal *and* con fast and pro fast *and* con thermal. For example, control of a fast reactor is difficult compared to a thermal reactor. It is inefficient to write this same information both as a pro for thermal and a con for fast reactors. The fifth and sixth cells eliminated the need to do so. If in doubt participants were encouraged to prioritise, writing down information rather than following too carefully the framework of the sheets.

The work area of Step 1 prior to the exercise and an example of a completed design element information sheet.



Following an initial rotation of contributing to the information sheets, participants took a 2 minute break to get a coffee or tea. With drinks in hand, they went through a second, more brief, rotation of the information sheets, starting with the same sheet as they did on the first rotation. This time they familiarised themselves with the information that the other members of the group had added. Where necessary they were welcome to add additional notes.

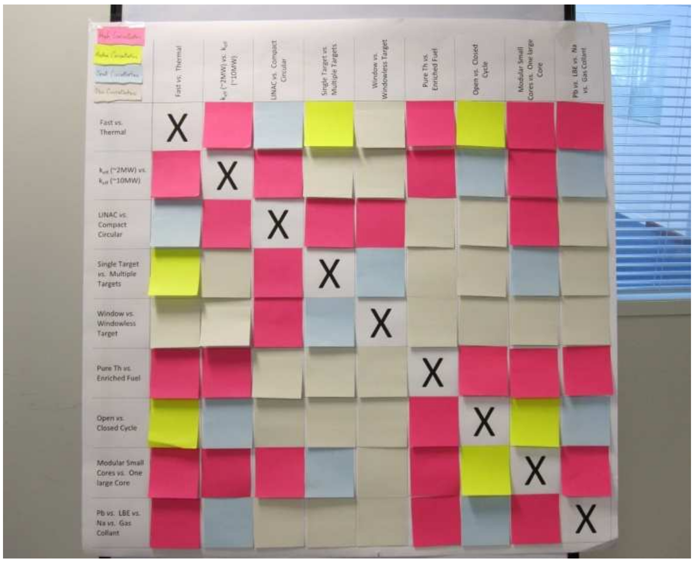
This body of information served multiple purposes: it engaged the participants, bringing a wide variety of ADSR design considerations to the forefront of their minds; it provided reference material for use during the remainder of the design exercise; and it catalogued interesting features of ADSRs for future reference. Details of all of the comments made on the Information sheets from Step 1 are appended to this document.

The Interaction Matrix

To reduce the complexity of the challenge of making design decisions in Steps 2 and 3 a design interaction matrix had been drawn up and completed (by two members of the group, L.V.N. Gonçalves and S.J. Steer) prior to the group exercise. This matrix listed the 9 identified design choices against one another in columns and rows. Colour coding was used to indicate the degree to which making a decision between options for one design element affected the decision that might be made for another design element.

Coloured post-it notes were used in the cells within the matrix. It was intended that the colour coding would be a traffic light system: red, yellow and green for strong, medium and mild inter-element interactions, respectively. Due to the availability of post-it note colours the system was: strong = pink, medium = yellow and mild = blue. If a decision over one design element had zero impact on another a grey note was used. The degree of correlation between design elements was therefore broken down into one of four categories. The interaction matrix did not constitute a step during the exercise in itself, but it was used to facilitate the latter two steps of the exercise.

The Interaction Matrix as used during the group exercise.



	Fast vs. Thermal	k_{eff} (~2MW) vs. k_{eff} (~10MW)	LINAC vs. Compact Circular	Single Target vs. Multiple Targets	Window vs. Windowless Target	Pure Th vs. Enriched Fuel	Open vs. Closed Cycle	Modular Small Cores vs. One large Core	Pb vs. LBE vs. Na vs. Gas Collant
Fast vs. Thermal	X	🟥	🟦	🟨	⬜	🟥	🟨	🟥	🟥
k_{eff} (~2MW) vs. k_{eff} (~10MW)	🟥	X	🟥	⬜	⬜	🟥	🟦	🟥	🟦
LINAC vs. Compact Circular	🟦	🟥	X	🟥	🟥	⬜	⬜	🟥	⬜
Single Target vs. Multiple Targets	🟨	⬜	🟥	X	🟦	⬜	⬜	🟦	⬜
Window vs. Windowless Target	⬜	⬜	🟥	🟦	X	⬜	⬜	⬜	⬜
Pure Th vs. Enriched Fuel	🟥	🟥	⬜	⬜	⬜	X	🟥	🟥	🟥
Open vs. Closed Cycle	🟨	🟦	⬜	⬜	⬜	🟥	X	🟨	🟦
Modular Small Cores vs. One large Core	🟥	🟥	🟥	🟦	⬜	🟥	🟨	X	🟥
Pb vs. LBE vs. Na vs. Gas Collant	🟥	🟦	⬜	⬜	⬜	🟥	🟦	🟥	X

Interaction matrix with a four tier colour code indicating the degree to which decisions in one design element affect the decision made for other elements

	Thermal *vs.* Fast	k_{eff}~0.995 *vs.* k_{eff} ~0.985	LINAC *vs.* Compact Circular Accelerator	Single *vs.* Multiple Targets	Window *vs.* Windowless Target	Fuel Composition	Open *vs.* Closed Cycle	Modular *vs.* a Single Large Core	Coolant Choice
Thermal *vs.* Fast	X	🟥	🟦	🟨	⬜	🟥	🟨	🟥	🟥
k_{eff}~0.995 *vs.* k_{eff} ~0.985	🟥	X	🟥	⬜	⬜	🟥	🟦	🟥	🟦
LINAC *vs.* Compact Circular Accelerator	🟦	🟥	X	🟥	🟥	⬜	⬜	🟥	⬜
Single *vs.* Multiple Targets	🟨	⬜	🟥	X	🟦	⬜	⬜	🟦	⬜
Window *vs.* Windowless Target	⬜	⬜	🟥	🟦	X	⬜	⬜	⬜	⬜
Fuel Composition	🟥	🟥	⬜	⬜	⬜	X	🟥	🟥	🟥
Open *vs.* Closed Cycle	🟨	🟦	⬜	⬜	⬜	🟥	X	🟨	🟦
Modular *vs.* a Single Large Core	🟥	🟥	🟥	🟦	⬜	🟥	🟨	X	🟥
Coolant Choice	🟥	🟦	⬜	⬜	⬜	🟥	🟦	🟥	X

🟥 **Strong Correlation**

🟨 **Medium Correlation**

🟦 **Mild Correlation**

⬜ **No Correlation**

Step 2 – Designing ADSRs to a Single Goal

It was recognised in advance of the group exercise that the multiple aims of ADSRs often act in opposition to one another. For example, it is desirable to increase the safety of the reactor to the highest possible level; however, sustainability is improved by reducing the back-end radioactive waste inventory. Methods for improving sustainability include operating a fast reactor, but this is less safe than the alternative, a thermal reactor. For this reason and many similar ones, it is challenging to adequately satisfy all of the design requirements.

It was envisaged by the participants that the time scale on which ADSRs may reach commercialisation will be comparable with those of Generation IV (Gen-IV) reactor concepts. It was therefore considered reasonable to design an ADSR against the same criteria as Gen-IV reactors. Before attempting to satisfy all of the Gen-IV goals simultaneously, simplified design scenarios were considered, where only one aim was considered at a time. During the exercise, the Gen-IV goals were grouped and simplified into 4 categories: Safety and Reliability, Proliferation Resistance, Economics and Sustainability. As a group the participants designed 4 ADSRs, each one satisfying as far as possible one of the 4 categories.

Summary of the Gen-IV goals as given by the Gen-IV Forum:
http://www.gen-4.org/PDFs/GIF_Overview.pdf

Sustainability-1 *Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and provides long-term availability of systems and effective fuel utilization for worldwide energy production.*

Sustainability-2 *Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.*

Economics-1 *Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.*

Economics-2 *Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.*

Safety and Reliability-1 *Generation IV nuclear energy systems operations will excel in safety and reliability.*

Safety and Reliability-2 *Generation IV nuclear systems will have a very low likelihood and degree of reactor core damage.*

Safety and Reliability-3 *Generation IV nuclear energy systems will eliminate the need for offsite emergency response.*

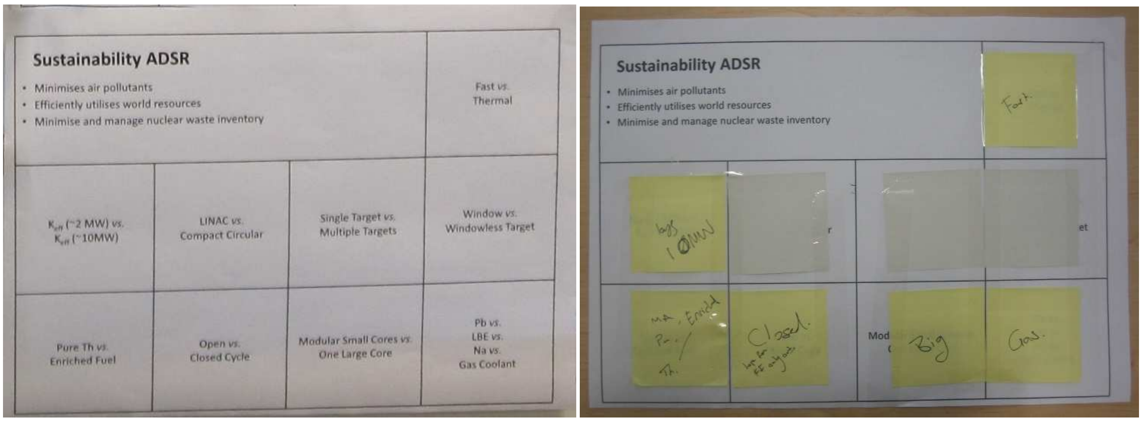
Proliferation resistance and Physical Protection *Generation IV nuclear energy systems will increase the assurance that they are very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.*

An ADSR that maximises sustainability was selected as the first to be designed. This decision was made as the group anticipated that it would be the easiest to design. A group consensus was reached regarding which of the 9 design elements most strongly benefitted sustainability. In the case of sustainability this was the fuel choice. A fuel that includes recycled minor actinides was selected as the most sustainable fuel. Having defined this design element, the group referred to the interaction matrix. The matrix indicated that the choice of fuel is strongly correlated with the choice of: a fast *vs.* thermal reactor; a k_{eff} ~0.995 or k_{eff} ~0.985; an open *vs.* closed fuel cycle; a modular *vs.* a single large core; and the coolant choice. In some cases the choice of a minor actinide fuel immediately defined the selected option for other design elements: for example, it is implicit that a reactor that burns recycled minor actinides operates with a closed fuel cycle. In other cases the decision to use a minor actinide fuel did not explicitly define the decision, however it did influence it. For example, in itself a k_{eff} value of ~0.995 or ~0.985 has only a marginal influence on sustainability, but in practice a fuel with significant quantities of minor actinides will only be controllable if it has a low value for k_{eff}. Here, the aim of sustainable nuclear energy has defined the fuel choice, which has in turn defined the k_{eff} value, even though k_{eff} itself does not have a strong direct influence on sustainability.

Some design elements were determined not to have a significant impact on the chosen parameter, nor was their design forced by the requirements of other elements. In these instances it was deemed unnecessary to select options for design elements that did not affect the chosen parameter.

Having designed ADSRs that each maximised their benefits to one of 4 sets of goals (sustainability, proliferation resistance, economics and safety), one more ADSR was designed. This fifth ADSR was aimed at being the fastest possible route to realising the first-of-a-kind commercial ADSR.

Photos from before and after the design of one of the five ADSRs intended to meet one goal, in this case, sustainability. Note: instead of quoting the k_{eff} value itself, sometimes the approximate proton beam power that the k_{eff} value would require was used during the exercise. Hence in this case k_{eff} ~0.985 has been termed "10 MW".



Sustainability ADSR

- Minimises air pollutants
- Efficiently utilises world resources
- Minimise and manage nuclear waste inventory

Fast *vs.* Thermal

K_{eff} (~2 MW) vs. K_{eff} (~10MW)	LINAC *vs.* Compact Circular	Single Target *vs.* Multiple Targets	Window *vs.* Windowless Target
Pure Th *vs.* Enriched Fuel	Open *vs.* Closed Cycle	Modular Small Cores *vs.* One Large Core	Pb *vs.* LBE *vs.* Na *vs.* Gas Coolant

Step 3 – Designing ADSRs that Meet all of the Design Goals

At this point five different ADSRs had been hypothesised, each meeting one of five design parameters: sustainability, proliferation resistance, economics, safety and the shortest route to deployment. For the third and final stage of the exercise these extreme designs were used to inform decisions for ADSRs that must consider all of the Gen-IV goals simultaneously.

Initially equal weight was given to each of the five design parameters. An ADSR, named the “Consensus ADSR”, was designed by selecting the modal decision from the previous five designs. For some design elements different options had been selected an equal number of times. This design approach also does not ensure that the final ADSR design is feasible. It is theoretically possible for incompatible options to be selected for different design elements. This happened not to be the case during the exercise. Although the Consensus ADSR did not resolve all design element decisions, it did provide an interesting insight into which design elements are preferential for satisfying the majority of design goals.

Three further ADSRs were designed during Step 3. Unlike the Consensus ADSR, these designs involved active input from the participants. A realistic scenario approach was used as a premise for each of the designs. The scenarios were nicknamed during the exercise as: “an ADSR for Britain”, ”an ADSR for the World” and “a European Fast ADSR”.

The ADSR for Britain was focused on the idea that the UK might independently develop its own reactor design. It emphasised the approach of concentrating on successfully integrating tried and tested systems, rather than facing even greater commercial risks by also pioneering new technologies.

The ADSR for the World concentrated on ensuring all countries have access to nuclear energy, whilst ensuring that such widespread use of nuclear materials minimises the risk of proliferation. It took account of the fact that some electricity grids are underdeveloped and that there are areas of the world where the population density and geographical constraints make large electricity networks prohibitively expensive.

The European Fast ADSR was based on the premise that there is widespread support and interest in ADSRs for developed countries’ electricity grids, therefore enabling the ADSR to be technically advanced compared to the other scenarios. This design took advantage of design options that the participants considered to require significant R&D. It also adhered to strong considerations as to the long-term sustainability of the design.

Design Decisions Made During the Exercise

In all, 9 different ADSRs were designed during the 2½ hour exercise. Each of these ADSRs considered options for 9 key design elements. The decisions that were reached are summarised below. Following the summary table brief descriptions of the reasons that led to the decisions are given.

It is worth noting that it was treated as a given that Th would form a part of the fuel mix. The advent of thorium as a fuel for electricity generation is a pivotal aim of the ThorEA Association.

Summary table of the selected options for the nine key design elements. Nine different ADSRs were designed, see the text for details on the motivation for each design

Design Element	Option for Element	Step 2					Step 3			
		Most Sustainable	Safest	Most Proliferation Resistant	Most Economic	Fastest Deployment	Consensus	For Britain	For the World	European Fast
Neutron Spectrum	Thermal		🟩		🟩	🟩	🟩	▨	🟩	
	Fast	🟩		🟩				▨		🟩
k_{eff}	~0.995			▨	🟩		▨	🟩	🟩	🟩
	~0.985	🟩	🟩	▨		🟩	▨			
Accelerator Type	LINAC	▨	▨	▨		*	▨	*		
	Compact Circular	▨	▨	▨	🟩		▨		🟩	🟩
Number of Targets	Single	▨		▨	▨				🟩	🟩
	Multiple	▨	🟩	▨	▨	🟩	🟩	🟩		
Window?	Window	▨	🟩	▨	🟩	🟩	🟩	🟩	🟩	
	Windowless	▨		▨						🟩
Fuel Composition	Pure Th			🟩						
	U Enriched Th		🟩			🟩	🟩		🟩	
	Pu Enriched Th	🟩 Both			🟩	🟩	🟩	🟩	🟩 *	🟩
	MA Enriched Th	🟩			🟩		🟩		🟩	🟩
Cycle Type	Open		▨	🟩	*	🟩	🟩	▨	🟩	
	Closed	🟩	▨					▨		🟩
Core Style	Small Modular			🟩					🟩	
	Single Large	🟩	🟩		🟩	🟩	🟩	🟩		🟩
Coolant	Lead			🟩				▨		🟩
	Lead-Bismuth Eutectic			🟩				▨		
	Sodium			🟩				▨		
	Gas (CO_2/He)	🟩	🟩					▨ *		
	Water		🟩		🟩	🟩	🟩	▨	🟩	
	Fluoride							▨		
	Heavy Water							▨		

🟩 Selected Option for a Design Element

▨ No selection made

**see text for details*

The Most Sustainable ADSR

The primary driver for the sustainable ADSR was that it should both waste as little fuel as possible and eliminate as much long-term waste as possible. It was therefore decided that the fuel composition should be Pu-MA enriched Th. This decision drove the need for the k_{eff} value to be low, in order to ensure that the reactor would be controllable. The fast neutron spectrum was selected, as it improves the efficiency of fuel consumption. A large reactor core allows for lower enrichment of the fuel, extending the lifetime of fuel reserves, and gaseous coolants ensure very low neutron activation of the coolant.

The Safest ADSR

The driving design feature was that this ADSR should operate in the thermal spectrum. This decision drove the choice of gas or water for the coolant, as these coolants are tried and tested for thermal reactors. A low value for k_{eff} (i.e. the highest possible accelerator power) was selected, thus reactor transients would be unlikely to cause prompt criticality accidents. U enriched Th was selected as uranium has the largest delayed neutron fraction among the fuel choices. Having many low powered accelerator beams was deemed to pose less of a risk than a single powerful beam: this prompted the selection of multiple targets. That decision implied the use of windows as it was not thought feasible to incorporate multiple windowless targets into the design. Having multiple targets also drove the decision for selecting a large reactor core, as it is considered infeasible to implement multiple targets into a small core module.

The Most Proliferation Resistant ADSR

The driving design element choice for this ADSR was to use pure thorium fuel. This ensures that the fuel does not pose a proliferation risk while in transit to reactor sites. Spent fuel would contain significant quantities of ^{232}U thus ensuring that the fuel could only be handled remotely for the first few thousand years after leaving the reactor. It was recognised at the time that the longer-term (many thousands of years) implications of using pure thorium as the fuel might lead to reduced proliferation resistance. A decision was made to place most emphasis on the proliferation resistance of the waste in the immediate millennium. This led to the choice of a fast reactor to ensure high a high abundance of ^{232}U in the spent fuel. An open fuel cycle would be adopted so that there is never any separation of any components of the spent fuel. Lead, lead-bismuth eutectic or sodium would be used as the coolant because they allow for the fast neutron spectrum. Although gas can do this too, a gas-cooled reactor was deemed more susceptible to physical attack than the other options.

The Most Economically Viable ADSR

For the most part the design choices for this ADSR did not strongly influence one another. As it is anticipated that the uranium price may rise significantly in the future, the fuel would be plutonium and/or minor actinides mixed with thorium. The thorium would not be reprocessed, thus the ADSR fuel cycle would be once through; however, the plutonium and minor actinides would have been derived from other sources. The thermal fuel cycle would be adopted as this technology is better developed than fast and it is tried and tested; a fast reactor would incur significant financial risk in demonstrating that it works. This decision then drove the choice of water as the coolant, as this is another tried and tested technology that is easily applicable to the thermal spectrum. A high value of

k_{eff} was selected, as this implies that the accelerator can be of a lower power, therefore reducing its expense. Compact circular accelerators were preferable, as it is anticipated that they will be cheaper than linear accelerators, despite the risk associated with demonstrating this technology. Large cores were selected as they are anticipated to be cheaper per unit power than modular cores.

The Nearest-Term Deployable ADSR

Selecting a thermal reactor was the primary driving factor for this ADSR, as fast reactors require significant R&D. Using uranium and plutonium fuels (for which there is a great deal of industrial experience) with the thorium would minimise unknowns in the character of the fuel. Selecting a low value for k_{eff} reduces risks posed by power transients. Linear accelerators were selected as this technology is more developed for high-power purposes than compact accelerators, however in this instance multiple lower-power ~600 kW accelerators would be preferable to a single large one. Windowed targets are more developed than windowless targets and were therefore selected. To reduce the pressure on windows multiple targets would be used, thus reducing the power density on the window. Adopting the open cycle removes the need to develop thorium reprocessing techniques and using water as the coolant allows for drawing on substantial industrial experience. A single large reactor would reduce the need for high levels of fuel enrichment.

The Consensus ADSR

Based on the previous five ADSR designs the consensus ADSR would be as follows (the number of designs that selected the chosen design option are given in brackets): The reactor would be thermal (3 out of 5), take advantage of some sort of enriched fuel (4 out of 5), adopt an open fuel cycle (3 out of 4), be a single large core (4 out of 5), cooled by water (3 out of 5), there would be multiple targets (2 out of 2) and these would have a window (3 out of 3). No consensus decision was reached regarding the k_{eff} value or the accelerator type.

The ADSR for Britain

An ADSR developed and operated in Britain could take advantage of its plutonium stockpile. It would therefore be Pu enriched Th. The accelerator system would be the same as that of the nearest-term deployment ADSR in that it would be multiple linear accelerators, each with a power rating ~600 kW. The k_{eff} value would be high, to allow for the accelerators to have a lower power rating. There would be multiple targets, each with a window. The reactor core would be large, as economies of scale are important to nuclear power stations in the UK power grid. No decision was reached regarding whether the UK would benefit from expanding its reprocessing industry to also deal with spent Pu-Th fuel (i.e. whether the open or closed fuel cycle would be adopted). Also, no decision was reached regarding whether the reactor should be fast or thermal; however, it was decided that the outcome of that decision should dictate the coolant choice.

The ADSR for the World

The ADSR for the world was designed with strong emphasis on ensuring proliferation resistance. It would therefore avoid the need for nations to carry out their own processing of fuel. This would be handled at a few central facilities. The Th would be enriched (type of enrichment not specified) at such facilities and then shipped to a reactor. Once spent, the fuel would be returned to the central facility. The fuel cycle would be open, removing the need for reprocessing. The thermal cycle and a high k_{eff} value (and thus a lower-power accelerator system) were selected, thus minimising the technical expertise required to operate the reactor. Due to the reactor being thermal, water would be used as the coolant. Reasons for not selecting the other coolants were: the dangers of pressurised fluorides, the proliferation risk posed by deuterium (heavy water) and the comparative greater experience with water compared to a gaseous coolant. Small modular reactors were selected as these were deemed to be more suitable to developing and small, remote electricity grids. This led to single targets being chosen. The reduced technical demands of a windowed target compared to a windowless design on a small core led to its being selected. Finally, compact accelerators were considered preferable to linear accelerators as they are expected to be simpler to operate; however, this final decision is subject to the success of R&D with compact accelerators.

The European Fast ADSR

The design of this ADSR is implicitly a fast reactor, the reasoning being that there is a strong European effort to manage nuclear waste inventories and promote sustainability using fast reactors. Enriched fuel was selected over pure thorium for economic reasons, and uranium enrichment was considered not to be desirable due to concerns about a possible rise in the cost of uranium in the future. The fuel cycle would be closed to benefit sustainability. A windowless target was deemed preferable and feasible within a large-scale European R&D programme. This would imply having a large reactor core and a single target. The large reactor decision is further backed by economies of scale arguments. The coolant would be lead, as a lead-bismuth eutectic is less sustainable due to limited bismuth reserves, and because less ^{210}Po is generated by a pure lead coolant. Pressure vessel concerns discounted a gaseous coolant as an option, and sodium was not selected due to the risks of a loss of coolant accident. Concerns regarding the feasibility of a high-power accelerator system resulted in a high k_{eff} value being selected. If it can be developed, a compact accelerator was considered preferable for its economic benefits; however, linear accelerators were considered acceptable if compact accelerator development is found to be poor.

Appendix – Contents of the Information Sheets

Tabulated below are the comments contributed by the participants to the information sheets during Step 1 of the exercise. A minimum number of changes have been made to the wording of the original comments. Those changes that have been made serve only to account for participants having used shorthand when writing their comments.

This list is not an exhaustive description of the pros and cons of the technology options for ADSRs. No additional pros or cons have been added to the list following completion of the exercise.

Some technology options were missed from the information sheets used in Step 1 (these were the water and heavy water coolant options). This was not due to an aversion of the group to consider them; they were neglected by error during the preparation phase. The pros and cons of these technologies were therefore not written down. They were still, however, considered during Steps 2 and 3. To compensate for the error participants drew on their personal understanding of the technologies and, when appropriate, dictated pros and cons to the group during these two steps.

Design Element	**Option for Element**	**Pro**	**Con**
Neutron Spectrum	Thermal	• Established technology • Better for transmutation of <u>some</u> fission products • Better for pulsed operation • Requires a lower level of enrichment • Generally more controllable than fast system due to longer neutron lifetimes • Easier to control reactivity changes *c.f.* fast	• Hard to beat the economics of thermal LWR • Requires a material to act as a moderator • Shorter fuel cycles *c.f.* fast • A physically big reactor • Less good neutron economy *c.f.* fast • Cannot control a ^{238}U thermal breeder
	Fast	• Better neutron economy • Smaller and cheaper to build • Can operate as a critical 100% Th reactor following initial enrichment • Better MA burn up • Could transmute waste	• Poor track record • Slower to equilibrium • Implies complex technologies for coolant • Safety is difficult: energy densities, voiding risks, speed of temperature transients
k_{eff}	~0.995	• Smaller accelerator • Makes possible integrated facility: (1) ADSR fuel preparation (2) beam off (3) critical operation	• Requires well characterised fuel, hence not good for “waste” incineration • Could be too close to $k_{eff} = 1$ to be of any value • Questions of maintenance of subcriticality if close to $k_{eff} = 1$
	~0.985	• Increased external neutron source enables use of fuel with poor neutron economy • Improved safety enhancement • Much easier safety case given margin against criticality excursions • Neutron spectrum will be slightly harder as more neutrons derive from the accelerator	• Far beyond accelerator state of the art • Reduced responsiveness to reactivity feedbacks • Limits the benefits of multiple accelerator redundancy gains • May not require multiple accelerators (save money), but will only one be reliable enough?
Accelerator Type	LINAC	• Established technology • Linear technology broadly demonstrated and costs predictable • Can produce necessary power levels • Less of a worker radiation hazard • EU support for them. R&D community exists • Linear accelerator allows for the possibility of using existing facilities?	• Very large • Linear accelerators likely to be prohibitively expensive • Questions remain about reliability and whether this can be adequately mitigated
	Compact Circular	• Modularity • Rare to lose 100% of beam due to modularity • Likely to be lower cost • Circular needs less land • Several developing options available, one may come through	• Not yet demonstrated – technical risks and less cost prediction • May never achieve required proton intensity • Practical implications of implementing redundancy are tough

Number of Targets	Single	• Simplicity, low cost (?) • Accepted standard configuration • Might be easier to deploy a demonstrator with only one target	• High (too high?) target energy density • More sensitive to beam losses • Power peaking inevitably less good • Beam splitting/merging might irradiate equipment if № targets ≠ № accelerators
	Multiple	• Easier to achieve required accelerator current and power • More uniform power distribution across core • Redundancy (compensation of beam loss). More uniform distribution of power	• More expensive • Question as to whether a multi-target system can tolerate loss of one beam without causing shutdown • Engineering solution more complex • Possible variation in power and fluctuation around the core • Beam splitting/merging might irradiate equipment if № targets ≠ № accelerators
Window?	Window	• Easier and more reliable target control system • Prevents the contamination of the accelerator tube	• Regular replacement required due to damage • Material selection is a problem • Not obvious window possible
	Windowless	• No need to change window • Permits higher-power accelerator options	• Greater contamination, radiation field and decommissioning burden in part from proton impact on Pb vapour • Potentially unreliable • Multi-target systems very challenging with liquid target • Harder to achieve an effective vacuum
Core Style	Small Modular	• Better Power Peaking • Mass production and testing in factories • Factory construction can be cheaper and is more reliable • Scalable size of plants, power rating flexibility • Lots of UK knowledge and capacity (Rolls Royce and BAE Systems) • Suits "sealed for life" cores, delivered to communities/nations as a black box and then taken away again • Easier to manage an efficient maintenance schedule • Modular suits off main grid developments: remote communities, islands	• Need for more accelerators (in some configurations) • Poor neutron economy – leakage • Higher enrichment needed due to small critical mass
	Single Large	• Economies of scale on auxiliaries (fewer larger turbines etc) • Overall cost per kWh better if bigger • Reduced MCC, cables, starters, instruments etc for equivalent power output • Better neutron economy critical mass	• Less uniform distribution of power • Poor power peaking or multiple accelerator-target configuration needed • Economies of scale counterfeited by increasing need for accelerator power

Cycle Type	Open	• Fuel resource (thorium) good for hundreds of years • Open cycle has good short-term (~100 years) proliferation resistance • Exportability of technology to developing world enhanced	• Increased waste • Need for source of initial enrichment if not willing to wait for ^{233}U to be bred • Movement of fissile material • Throwing valuable energy rich materials away • Uranium open cycles have bad long-term (~1000 year+) proliferation resistance (^{239}Pu). What about thorium?
	Closed	• Fuel resources available for ~infinite time • Reduced waste production • Increased fuel sustainability	• Closed cycle requires "P5" weapon state or need for international facilities and militarised international transport • Need to move Pu and 233U around – transport proliferation risk • Global increase in proliferation vulnerability of cycle • Reprocessing needed • Large uptake of closed cycle requires more "Sellafields". Cost of developing industry
Fuel Composition	Pure Th	• Ideal for counties that don't have a Pu/^{235}U stockpile • Very low proliferation risk before cycle begins. Afterwards (?) • Reduced actinide production • No need to transport Pu etc • Sustainability	• Needs time with beam on before it starts generating power (~month thermal, ~many months fast) • ^{232}U and ^{229}Th emit highly radioactive legacy radiation. • Not directly fissile, poor neutron economy • Production of Protactinium • Small delayed neutron fraction *c.f.* ^{235}U • Large variation in k_{eff} with associated control ramifications
	U Enriched Th	• Mixed U content gives good proliferation resistance at the backend • Possible extended fuel cycle compared with ^{235}U-^{238}U	• Requires the use of centrifuges etc for enrichment. Potential for these to be abused. • Heavy actinide production • Limited ^{235}U resource • Cost of enrichment • The fuel cycle relies on the uranium component, therefore little benefit over pure UO_2 fuel use (~10%) • Fresh fuel may need military levels of security. If little ^{238}U is used it is more of an issue than Pu-Th.
	Pu Enriched Th	• No waiting time to generate fissile material • Reduces Pu stockpile • Good balanced criticality in fast spectrum	• Will require stockpile or reprocessing • Cost of enrichment is added to total cost • Once through produces higher toxicity from ^{233}U • Fresh fuel would require military levels of security
	MA Enriched Th	• Increases fuel sustainability • Reduces existing MA stocks	• Requires new advanced reprocessing techniques for MA-FP Separation (?) • Can produce even heavier actinides (Perhaps?) • Small delayed neutron fraction • Blurs the policy that MA are "waste" not "fuel". Requires a policy change?

Coolant	Lead	• Reduced ^{210}Po production *c.f.* LBE • Good reflector of neutrons • Can enrich the ^{208}Pb content leading to very low neutron absorption • Good void coefficient properties • Not likely to experience a loss of coolant accident	• Solidification problem due to high melting temperature (higher than for LBE) • Needs to operate at a higher temperature than other coolants • Steel corrosion
	Lead-Bismuth Eutectic	• Not likely to experience a loss of coolant accident • Thermal properties are good • Lower temperature of operation *c.f.* lead • Improved corrosion resistance *c.f.* lead due to lower operating temperature • Easier core head access – lower metal vapour pressures (?)	• Suffers corrosion issues, albeit less than lead • Leads to the production of ^{210}Po • Bismuth is not a plentiful resource
	Sodium	• Can spate ^{233}Pr online and return it once it has decayed into ^{233}U fuel • Large operating experience	• Softer neutron spectrum *c.f.* liquid heavy metals. Soft spectrum is less good for waste transmutation • Limited mass flow rate • Need a separate cycle for coolant • Sodium fire at Monjou • Need to avoid Na + H_2O interaction • Re: LOCA or Local Coolant Voiding, positive void coefficient thermal run away • The biggest risk is from a (n,gamma)^{24}Na leak, due to the gamma emissions of ^{24}Na
	Gas (CO_2/He)	• Lots of UK experience in gas cooled technology (MAGNOX, AGR) • Increased visibility of core interior • Nearly zero neutron absorption • Can be heated to very high temperatures – better thermal efficiency • Fuel element injection is easier (No draining)	• Potential for rapid loss of coolant, followed by meltdown • Pneumatic explosion hazard • Need for high pressure (40 bar) pressure vessel. This is difficult to seal
	Water	See text above table	See text above table
	Fluoride	• Molten Salt is good for partitioning and transmutation applications (?) • Good neutron economy can operate as a critical thermal thorium breeder • Controllability enhanced by de facto steady-state operation • Much improved tolerance of thermal transients (caused by beam loss)	• Little experience, lots of technical risk • Online reprocessing will be difficult to establish effectively
	Heavy Water	See text above table	See text above table