CHALLENGES AND OPPORTUNITIES FOR FLEXIBLE NUCLEAR GENERATION

PRELIMINARY ASSESSMENT OF FERTILE INSERTS FOR IMPROVING CONTROL ROD WORTH IN PWR CORES

By John Jones[1], Andrew Buchan[2] and Ali Tehrani[2]

SUMMARY

- Our hydrocarbon-based economy poses a significant risk to the Earth's climate by continued emission of carbon dioxide and methane. Mitigating these impacts requires a transition away from fossil fuels. Achieving transition is expected to require a substantial increase in electricity generation alongside extensive electrification of energy uses.
- Renewable energy sources, particularly wind and solar, will play a key role in a net-zero electricity system, but in periods of calm weather, gas turbines currently generate our electricity. Nuclear power offers a low-carbon alternative, but replacing gas-fired generation but will require nuclear reactors that operate in a load-following mode to meet varying demand. Emerging Small Modular Reactor (SMR) designs are promising candidates but would benefit from some design changes.
- This article reviews the UK's projected future electricity demand, the anticipated energy mix, and the associated system vulnerabilities during the transition to net-zero. The role of renewable technologies and hydrogen is considered alongside nuclear power. Design modifications to SMR cores could enhance their capability for load-following operation. Increased control rod worth and improved axial stability are desirable. Indicative analysis is presented to show that modest design changes, including reduced core height and the use of fertile rod inserts, can improve axial stability while increasing control rod worth by approximately 9% relative to conventional designs, even without changes to the fuel assemblies characteristics key design features.

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INTRODUCTION

Increases in global temperatures are already having adverse effects on countries that are particularly sensitive to climate change. Social dislocation, war and migration are expected consequences [1]. It is generally recognised that limiting climate change by reducing carbon dioxide (CO_2) emissions is better than dealing with the consequences of change in these regions.

A rational approach to limiting climate change starts with considering our current use of fossil fuel and the potential to change. This includes examination of trends and consideration of strengths, weaknesses and opportunities.

In this context we need to examine; the energy market and the role that nuclear power can play, then consider the obstacles and how they can be overcome. The intent is to point the way to possible areas for future work.

THE UK ENERGY MARKET

The makeup of the UK energy market is illustrated in Figure 1. Over recent years the UK has transitioned from burning coal to natural gas for domestic heating and electricity production. Transport has been largely fuelled by oil [2], with a gradual reduction in oil consumption mostly caused by improved efficiency of its use, but also through the adoption of electric cars. Nuclear power continues to support baseload electricity production.

Natural gas

The burning of natural gas has been claimed as a step in the right direction, but while it reduces the amount of CO_2 emitted during combustion, methane is itself a very potent greenhouse gas. The UK government has undertaken measures to reduce methane release from pipework supplying domestic housing by replacing corroded steel pipes with polythene [3], but methane levels continue to rise globally and while methane has a shorter lifetime than CO_2 in the atmosphere, it is much more efficient at trapping thermal radiation. Per unit of mass, methane has a warming effect about 80 times more potent than CO_2 over 20 years, with an even greater impact in the short term. It has been estimated that methane is responsible for 30% of total global warming since the industrial revolution and is the second largest contributor to global warming after carbon dioxide [4]. An effective climate maintenance strategy needs to reduce the consumption of fossil fuels and the associated methane emissions.

Wind

In recent years the UK has seen a notable increase in energy generation from wind. We have made a start at decarbonisation and energy policy aims to accelerate this. Domestic heating can be achieved using air-source heat pumps and increased use of electric vehicles can support transport long term strategy. In essence, we can run a modern economy by electrical power distribution.

Hydrogen

There is talk about the use of hydrogen as a replacement for natural gas, but the concerns are numerous: Hydrogen is prone to detonation [5]. In addition to this it is arguably not containable within our existing gas infrastructure because it "skips" through interstitial voids in polymers [6] and causes embrittlement as well as permeation through defects in steel piping.

Leakage of hydrogen is a serious concern. Whilst hydrogen is not a

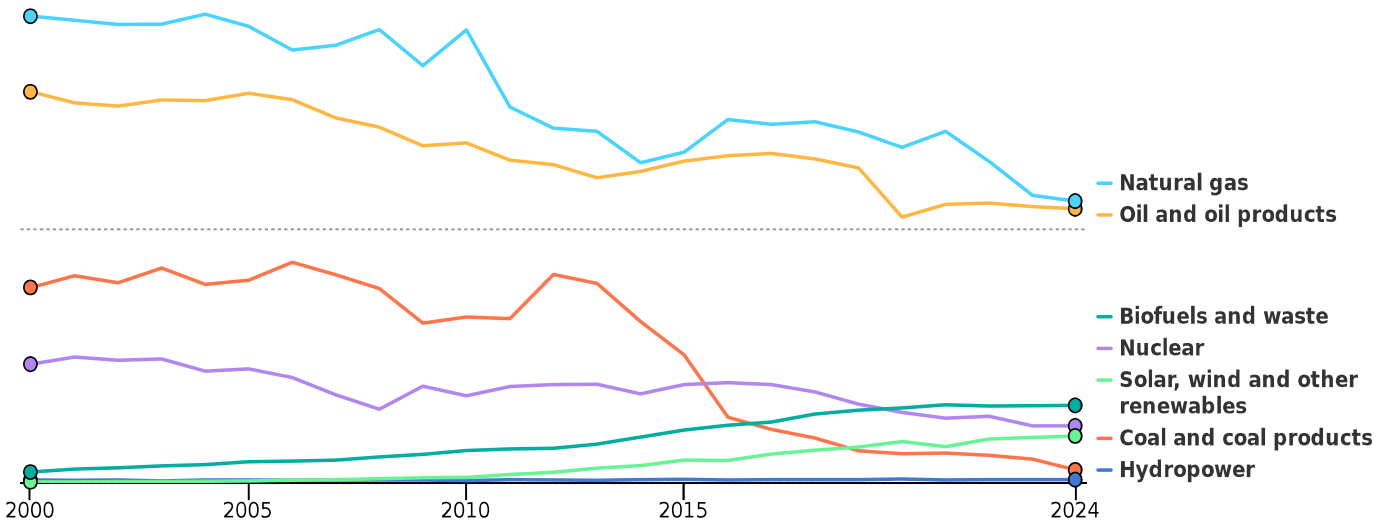


FIGURE 1: UK Energy Market Share [1]

strong greenhouse gas, it affects the atmospheric chemistry, reducing hydroxyl radical (OH) concentrations, a principal sink for methane. Anticipated levels of hydrogen release will increase the lifetime of methane in the atmosphere, leading to further adverse effects on climate [7].

While hydrogen will have a role in our energy mix, the safety and environmental concerns outlined above suggest that hydrogen facilities should have secondary containment where reasonably practical and be robustly regulated.

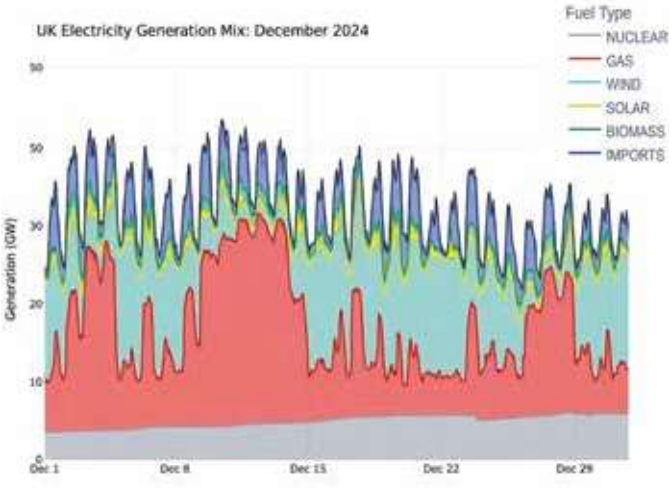


FIGURE 2: The Electricity Market

THE UK ELECTRICITY PRODUCTION

Given that electricity is likely to predominantly provide for our future energy needs, it is necessary to examine the electricity market.

Figure 2 illustrates the UK hourly energy mix over the period of a month (for convenience December 2024). Note that solar power does not make a significant contribution at this time of year [8], but wind and gas do.

The most striking aspect of these data is the daily variation in power generation. It provides a challenge to the management of the electricity supply grid. This is mitigated to a small degree by energy storage, but the bulk of the variation in output is achieved by modulating the output of gas turbines.

Nuclear power provides a base load, and its output is largely not modulated to follow daily demand.

Note also that the UK can broadly meet the need to generate electricity by the output of its wind turbines on a day when the wind blows, but having taken a month at random, we observe a period of a week where there is a wind drought. During this period the system is primarily reliant on natural gas to meet our energy needs and we pay consumers not to use electricity.

The length of wind droughts is variable, and the duration of a drought is shown in Figure 3 as a function of return frequency. It seems that we need to plan for a month over which UK wind will not make a significant contribution to our energy needs [9]. This is far too

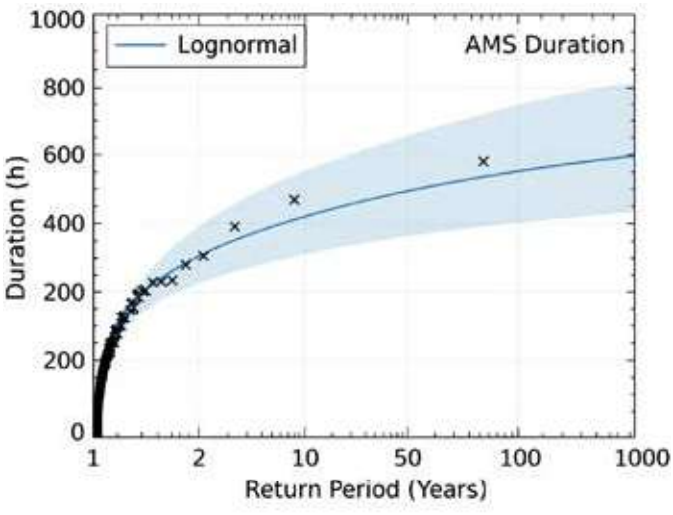


FIGURE 3: Wind Drought Duration & Frequency

long for energy storage to be relevant so the question becomes; what power generation can be used as part of a wind power system if not gas?

Nuclear power is an established reliable technology and can potentially fill this role but some changes to existing plant are desirable.

THE CHALLENGE FOR NUCLEAR PLANT DESIGN

Widespread use nuclear power stations poses both economic and technical challenges.

Economics

The conventional large power station has demonstrated its ability to safely and reliably generate electricity in baseload and load following operation. If the electricity market is to expand to supply our transport and heating needs, simple scaling of current energy demands suggests the capacity of the civil nuclear fleet would have to increase by up to factor of about four, just to maintain its market share [10]. Funding for this investment will require the nuclear industry to recover its reputation for reliable construction of power stations. Not only do they need to be safe but also built to time and cost.

Historically, the increased threat from larger aircraft and the desire to practically eliminate releases of radiation have led to designs with increased quantities of reinforced concrete until they reached the order of a million cubic meters per station. This made the construction of the nuclear power station a large civil engineering project and, like many such projects, the schedule became subject to delays and financial challenges.

The industry has responded to this problem by reducing the size of the containment building of a LWR to a level where it can be fabricated as a steel shell and the footprint of the facility has been reduced to that of a fairly modest building. Figure 4 is an illustration of the Westinghouse AP300 design, which is a power station small enough to fit onto half of a football field [11] but can supply power to a substantial town. The Rolls Royce SMR is slightly larger but also benefits from a modest building. The discussion that follows focuses on LWR PWR designs and modification for supporting our net-zero ambitions. Although Boiling Water Reactors can also meet these requirements, they have been omitted from the discussion solely to limit the scope of this paper.

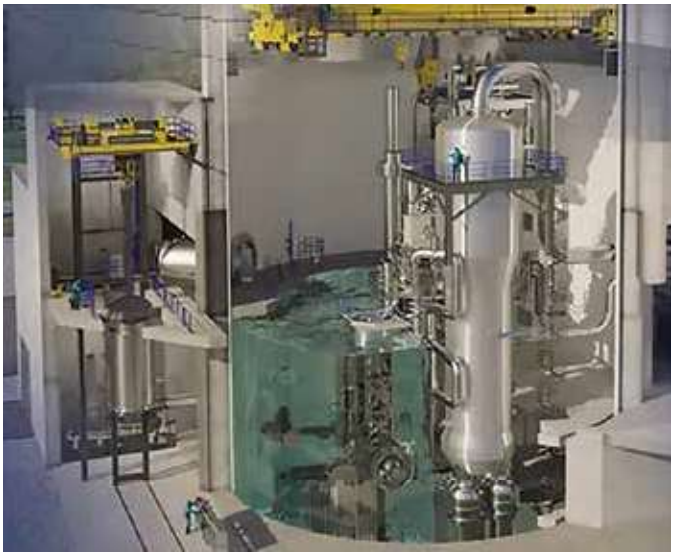


FIGURE 4: Illustration of the AP300 Design

The size of the containment building is determined by its ability to contain potential coolant leaks. Its volume is minimised by reducing the mass of coolant in the primary circuit and by increasing the rate of condensation of steam, should that coolant leak into the containment space. Steel structures and additional water sources assist in limiting the design pressure of the containment building and heat removal in faults by passive means can reduce the amount of auxiliary equipment needed.

Inevitably this reduction in the size of the facility has resulted in a reduction in power output, but the change has not been as large as many expected.

The move away from a large civil project (requiring a prolonged construction schedule) will itself increase confidence of potential investors, but designers have taken further steps to reduce the uncertainty of the plant commissioning phase. Whole systems will be constructed on skids in a factory and tested as modules before shipping them to site.

Finance of time spent commissioning is particularly expensive and the use of qualified modules should substantially cut this cost.

Load Follow

It is reasonable to expect that the small modular reactor will ultimately result in a substantial saving in the cost of nuclear generation and improve the availability of finance. However, to largely replace natural gas generation, it will be necessary to load-follow as the fluctuations in energy demand and wind output occur beyond the capability of battery storage for a foreseeable future.

Existing Generation III reactors have difficulty in following demand. The massive power output of a single unit would dominate local energy supply, and its loss would introduce a substantial perturbation to the electrical power distribution system should a unit trip. Engineers responsible for electricity distribution are cautious about how these units are used if there is a local shortage of power generation.

Even when the large units are required there are technical problems that can prevent their use.

Axial Power Stability

The core size of existing reactors has been optimised to maximise power output and consequently the core is only marginally stable to xenon transients at the end of a cycle of operation. The axial power profiles in a typical PWR at the beginning, middle and end of a fuel reload cycle (BOC, MOC and EOC respectively) are shown in Figure 5 [12].

At the end of a cycle (EOC) there is fairly loose coupling between the power peaks at the top and bottom of the core and this leads to problems with control of power shape. In order to retain control of the local power level, limits on control rod movement become necessary and the rate of change in overall power level is also constrained.

The power shape can be improved to some degree by axially zoning neutron absorbing material (burnable poisons) to flatten the initial power profile slightly, but the effect that can be practically achieved is limited (Figure 5).

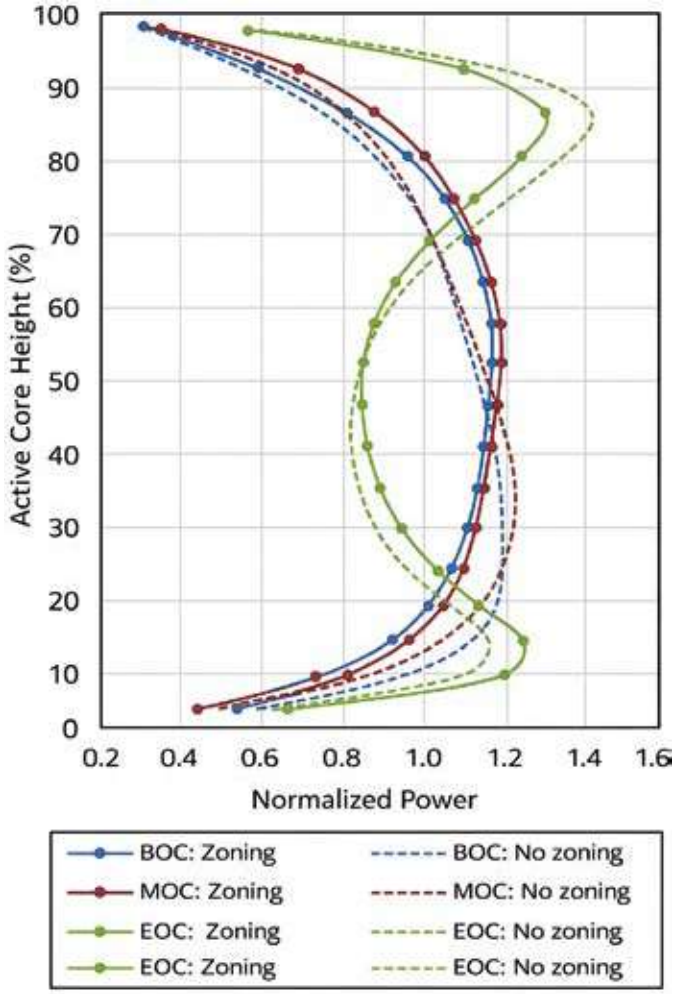


FIGURE 5: APR1400 Core Axial Power Profile

The best and most obvious means of improving axial stability is to reduce the core height. Some SMR designs have implemented this and benefit not only in terms of core stability, but they also have reduced coolant inventory. Obviously, the core volume is reduced, but the size of the volume occupied by the control rods is correspondingly reduced and so is the pressuriser volume. These reductions have a direct impact on the size of the containment building and hence the facility.

This change in core size goes a long way to support achieving the desired stability.

However, it also makes sense to reduce the reactivity of the fuel at the end of the fuel pins by reducing the fuel enrichment in this region. This is a well-established technique and is used to address the effect on local power peaks naturally found at the ends of the fuel pins, where thermal neutrons are reflected back into the core.

The power profile in a core where both of these mitigation measures have been taken is shown in Figure 6 [12].

Here the most reactive region of the core remains near the centre and movement of the power distribution in transients is much reduced, allowing control rods to modulate power levels with fewer constraints.

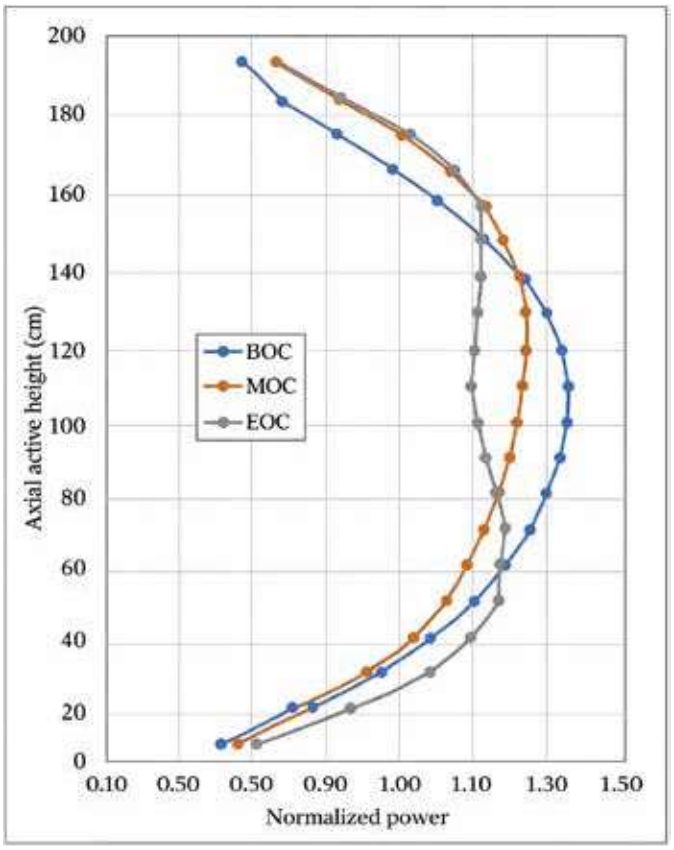


FIGURE 6: Core Axial Power Profile 2m Core

Improvements to Control Rod Worth

Having achieved adequate axial stability, the next task is to provide adequate reactivity control to keep the reactor critical at the required power level.

In current reactors there is often insufficient worth in the control rods to load-follow of over the entire power range without varying the concentration of boric acid in the coolant. This Dilution effect cannot always be achieved on the desired timescales.

Load follow over the entire power range requires an increase in the control rod worth so that changes in moderator density (associated with changes in power) can be accommodated and that the reactor can be safely shut down.

There is an obstacle that needs to be overcome to facilitate this. The fuel also needs to be made more resilient to changes in stress associated with local reactivity changes around the tip of control rods. However, modest changes in the fuel pellet composition can accommodate this and also reduce the release of fission products in fault scenarios [13].

With the current control rod assembly designs, there is a limit to the rod worth imposed by the size of the control rod drive mechanism and the geometry of the guide tubes in which the rods move. However, the adoption of accident tolerant fuel can allow a tighter fuel pin pitch and a correspondingly larger guide tube [14], so new fuel assembly designs are now possible.

With more of the moderator displaced by the control rod, the worth of the rod would be increased. Here we propose to go a step further

and place fertile inserts into the guide tubes of assemblies adjacent to the controlled assembly to displace the moderator in these locations.

This approach can be used to manage local reactivity in fresh fuel assemblies (instead of burnable poisons) and also to increase the importance of the guide tubes in the controlled assemblies.

This is similar to the control of reactivity using wet annular burnable assemblies (WABA) [15] and we envisage that these would be the basis of a design.

Significant changes to the geometry of fuel assemblies would be costly and cannot be achieved in the short term, but fertile inserts can be used now based on existing tooling designed for WABA.

The following analysis is based on fuel assemblies used in large-scale light water PWRs, but which are directly representative of those adopted in modern PWR-type SMR concepts. The effect of inserts on the flux profile in a current fuel design is illustrated in Figure 7. This assumes the use of depleted uranium (DU) as the fertile material, but it could equally be natural uranium or thorium. The effect initially relates mostly to removing moderator.

The colour map shows the spatial distribution of thermal flux in a supercell representing part of a cluster of 17 by 17 PWR fuel assemblies. Reflective boundary conditions are applied at all edges of the region illustrated; creating a domain representative of the centre of a typical reactor core; the region of high importance.

The quarter assembly occupying the bottom left of the domain is that of a standard design containing guide tubes with control rods withdrawn. The two half assemblies (top-left and bottom-right) and the full assembly (top-right) are designs with inserts included in the guide tubes.

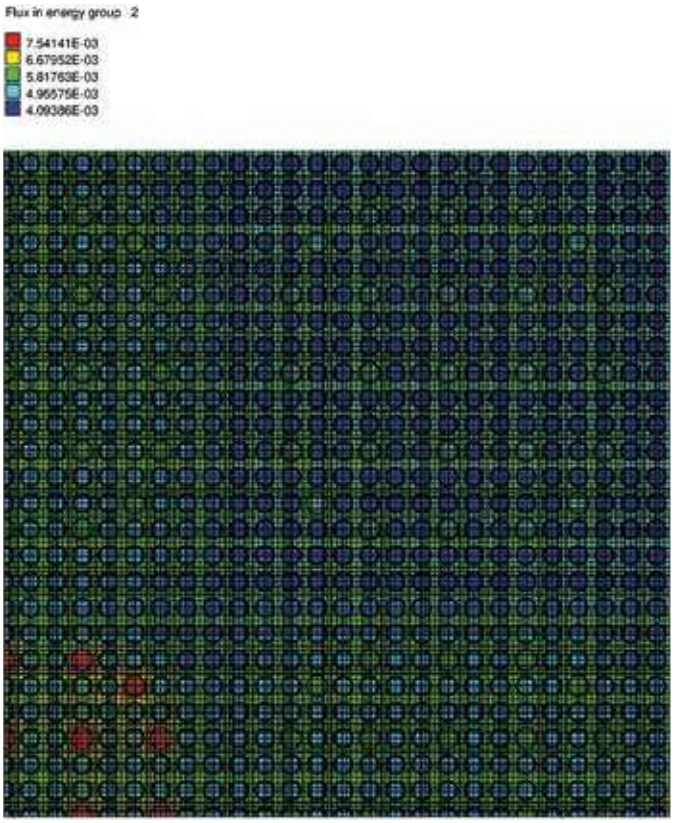


FIGURE 7: Thermal Flux – Un-rodded Supercell

For simplicity, the core is assumed to contain fresh fuel. The controlled quarter-assembly and the diagonally opposite full assembly have 5% enrichment, whereas the half-assemblies are enriched to 4%. This sort of arrangement could be used for a first core loading, after which the 4% enrichment would be replaced with second dwell assemblies.

The calculations were performed with SCALE6.1 in 2D transport mode using NEWT with the 238-group ENDF/B-VII.0 Library in accordance with [16]. The geometry and meshing are shown in Figure 7.

The thermal neutron flux exhibits high peaks around the control rod guide tubes of the assembly without the inserts. However, these peaks are dampened in the assemblies over regions containing the inserts.

The effect of the inserts on reactivity is summarised in Table 1. The reactivity of the region studied is reduced by 5000 pcm and the control rod worth is increased by 540 pcm. These changes are modest but still useful to the core designer.

Start of Cycle Rod Worths			
Conventional core K		With DU Inserts K	
all rods out	1.44	DU all rods out	1.39
all rods in	1.39	DU all rods in	1.33
Worth (pcm)	4710	Worth (pcm)	5250

TABLE 1: ROD WORTH SENSITIVITY

If small modular reactors are to expand the role of nuclear power, there will be a need for innovative core design. Whilst some initial analysis towards this objective has been presented here, further exploration of the wider design space would benefit from a new generation of modelling approaches. Fast surrogate models, which have received significant attention over the past decade, are particularly attractive for this task. They are capable of generating solutions to the neutron transport equation with accuracy comparable to high-fidelity models, but at a fraction of the computational cost. This enables efficient exploration of large design spaces to identify optimal reactor configurations; such work is currently ongoing by the authors.

CONCLUSIONS

Net-zero carbon emissions is an achievable objective and if wind power is to make a contribution, there is a need for a complementary technology to produce electricity when the wind is not blowing.

The small modular reactor promises to be able to meet the need to increase our base-load generation capacity in the short term and to increasingly displace gas-fired generation through load-following operation when wind output falls or is not available.

Some changes to the reactor core are required to permit load-following over an increased fraction of the fuel reload cycle, and there is scope to benefit from recent innovations in fuel design. To support this capability, modest modifications to existing fuel assemblies can be used to increase overall rod worth, which is desirable for enabling more frequent and flexible changes in power output. In particular, preliminary analysis presented here indicates that the introduction of fertile inserts can potentially increase overall rod worth by

approximately 9%. Further improvements are likely achievable through future investigation and optimisation. Future work should also examine the implications of such design features on operation and safety under load-following conditions.

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