A Symbiotic Approach to Compact Fission and Fusion Reactors

Richard J Pearson[a]*, Michael J Bluck[b] & Samuel T Murphy[c]

[a]*Department of Engineering & Innovation, the Open University, Milton Keynes, UK, richard.pearson@open.ac.uk*
[b]*Centre for Nuclear Engineering, Imperial College London, London, UK, m.bluck@imperial.ac.uk*
[c]*Department of Engineering, Engineering Building, Lancaster University, Lancaster, UK, samuel.murphy@lancaster.ac.uk*

INTRODUCTION

Given that both fission and fusion involve the production of energy by nuclear reactions, it is not surprising that many of the challenges faced by the associated technologies are similar. Since the first commercial fission reactor began operation in the 1950s, nuclear power stations have increased in size to exploit assumed economies of scale. Larger reactor designs have high capital costs and long returns on investment, and are thus not conducive to private venture. This, alongside other issues principally relating to safety, has sparked widespread effort to pursue small modular fission reactor designs (SMRs), which look to exploit efficient manufacturing processes, technological learning and modern financing.

Similarly, in the quest to demonstrate net energy gain the size of fusion reactors has also increased over time, though for the need to accommodate large magnets needed to achieve sustainable plasma conditions and to mitigate engineering limitations. However, the emergence of high temperature superconducting (HTS) magnet technology is widely anticipated to enable reduction in the size of magnets required for fusion devices, potentially opening a pathway to smaller fusion power plants in the future [1-4].

Albeit that the two nuclear technologies are at different stages in commercial development, both are ostensibly undergoing a revolution whereby smaller size may offer the opportunity for rapid and cost-effective development. However, this development comes with a series of new challenges that must be solved independently or cooperatively. Just as fission SMRs undergo commercial development based on knowledge from their larger counterparts, lessons learned from the upcoming SMR programme could be used to inform the development of compact fusion, with a view to adopt engineering solutions, and economic and regulatory framework.

Here we present an overview of some of the shared technological, economic and logistical challenges and opportunities ahead for both compact nuclear technologies, to identify the areas in which there are prospects for shared future development.

It is important to note that in this summary, the term "compact nuclear" refers to physically smaller fission or fusion nuclear reactors of lower power output (in the order of hundreds of MWe), when compared to large fission reactor technology (which is in the order of GWe).

Advances in Compact Nuclear

Several changes in the nuclear industry have triggered fresh interest in SMRs. Concerns regarding the safety of nuclear energy following the incident at Fukushima have prompted a re-evaluation of fully integrated concepts with the aim of limiting the likelihood of serious accidents. Further factors include the desire to reduce the capital cost associated with nuclear energy, and to allow for flexible operation through low power production or cogeneration.

As a result, a wealth of SMR designs have emerged, embracing the full gamut of fission technologies, including: water cooled; high temperature gas cooled; and liquid metal cooled designs, as detailed in [5, 6]. Closest to market are those that borrow from traditional pressurized water reactors (PWRs), for example market entry for the NuScale SMR is anticipated between 2025 and 2030 [5, 7]. Indeed, more advanced designs may take longer to develop but offer further advantages such as the burning of nuclear waste [8].

For fusion, magnetic confinement is regarded as the most likely pathway to commercial energy. The ITER reactor currently under construction in France is expected to demonstrate net energy gain around 2035, and is seen as the next step on the pathway to fusion energy [8]. However, ITER will not produce electricity, and nor will its successor "DEMO" (which at best estimate will be commissioned in the 2040s). Though DEMO is expected to be the final step towards a commercial fusion reactor, commissioning a power plant based on DEMO before 2050 is unlikely.

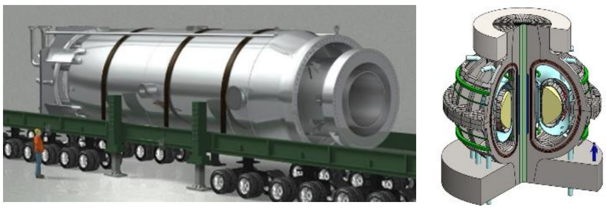

Fig. 1. For scale: NuScale's fission SMR (left) [7] and MIT's ARC Fusion Reactor (right) [2]

However, the timely emergence of HTS magnet technology is expected to provide a shake-up by potentially enabling the use of smaller, high-field fusion reactors [1-4]. The Massachusetts Institute of Technology (MIT) "Affordable Robust Compact" (ARC) reactor concept is a conventional tokamak which will explore the use of high field HTS magnets [2, 4], whilst Tokamak Energy Ltd are targeting electricity production from fusion by combining the same HTS magnet technology with the promising physics basis of the Spherical Tokamak [9]. Though at an early stage, if successful, these initiatives may result in the realization of fusion energy sooner [4].

Shared Engineering Challenges

While both compact fission and fusion reactors face independent and unique engineering challenges, many of the systems will be inherently similar and thus may benefit from being solved through collaboration. Key to advancing innovative reactor designs in both fields is the development of appropriate nuclear materials, as many compact reactor concepts are likely to subject materials to similar high temperatures and levels of radiation for longer periods than current nuclear reactors. In the case of fully integrated fission SMRs, the core of the reactor will be inaccessible during operational life, therefore any material failures may be difficult to ameliorate. By contrast, the ARC fusion reactor is designed to be deconstructed to enable maintenance and replacement of key components [2]. Despite the benefits, this will be expensive and will present an additional safety hazard, thus further development of durable radiation resistant materials is essential.

There are a range of studies examining materials issues for future fission [10], and some that address SMRs specifically [11]. Numerous studies address materials challenges for future fusion devices [10, 12], but beyond reference to the challenges in [2] and [4], very little research into materials issues specific to compact fusion reactors exists. Encouragingly though, there is strong evidence of a mutual approach to the development of structural materials for both fission and fusion reactors and thus potential for future shared activity [10]. The development of structural materials for all types of future nuclear is much the same, despite the greater displacement damage and temperatures expected in fusion reactors (which will likely be even greater in compact fusion reactors). The amount of upcoming cutting-edge research needed supports the notion that all nuclear materials research significantly contributes to the wider field of materials for use in extreme environments, not least nuclear. A prime example is in that materials for fusion reactors are being judiciously selected and developed to lessen the quantity of long-lived nuclear waste generated. Though this may prove expensive, collaboration from both nuclear communities in this area offers a route to not only further technological proficiency, but also to improving public image.

The use of tritium as a fuel for future nuclear fusion reactors adds numerous complications. In addition to the neutron damage caused by high energy neutrons from the deuterium-tritium (D-T) fusion reaction, tritium is difficult to handle and readily interacts with certain materials, producing tritiated waste which must be dealt with. Furthermore, retention of tritium in materials affects efficiency of tritium fueling and thus hinders overall reactor performance [13]. There are also issues in the supply of tritium for fusion, as future research devices will depend on the CANDU-type fission reactor as the only existing commercial source of tritium. Only limited amounts of CANDU tritium will be available for use due to low production rates, the steady shutdown of the global reactor fleet, and decay of the tritium stockpile [14]. Nevertheless, CANDU tritium is critical for fusion until effective tritium breeding technology can be demonstrated (for which there are also opportunities to collaborate, as tritium breeding technology shares many parallels with molten salt fission reactor technology [15]), as no fusion reactor can depend on an external source of tritium for commercial operation.

Economics of the Compact Approach

The deployment of compact nuclear technologies will to a large extent be dictated by economic concerns. Several studies have compared the economic viability of SMRs with Large Reactor technology, and conclude that SMRs can be economically viable [6, 16]. Whilst the general view is that larger reactors benefit from efficient use of raw materials, unique set-up costs (licensing, civil works etc.), and thus lower capital costs, the argument for economies of scale is only applicable when comparing against build of a one-off SMR. On the contrary, important factors in which large-scale nuclear reactor technology rarely capitalizes on, such as standardization of design, bulk production, and design improvement through technological learning is shown to outweigh the effect of economies of scale [16].

SMRs are intentionally designed to reduce capital costs and corresponding financing costs by exploiting the factors above, as well as through shared Balance of Plant in modular power plants. Unlike France with its partially state-owned energy utility, nations that adopt deregulated energy markets commonly struggle to afford financing for capital-intensive nuclear projects, which can make up more than 40% of total capital cost [6]. The reduced capital cost of lower power output SMRs may offer more affordable capital financing options, as well shorter lead times through improved logistics, and shipment as fully pre-fabricated modules.

As alluded to, SMRs have been designed with marketability in mind, and value the importance of a standardized design, manufacturing and commissioning process from conception. Standardization, one of the keystones of the SMR concept, has already proven effective in the nuclear industry. Through analysis of data of reactors built in France from 1978 to 2002, Rangel and Leveque observed cost reduction in constructing multiple reactors of the same type, regardless of reactor size, showing evidence of technological nuclear learning [17]. Interestingly, the same study also found that construction costs increased in line with increased reactor power output (and thus size)

[17]. The trend observed was deemed to be due to the increased complexity associated with managing large-scale engineering projects.

Though SMR companies such as NuScale are innovating in standardization [7], compact fusion initiatives are also considering ease of manufacture and serviceability as key design drivers [2-4]. Though neither has undergone practical assessment, some hypothetical analyses on the economics of larger future fusion power plants exist, but comparatively fewer are available on the economics of compact fusion power plants [2, 3]. However, it is reasonable to assume that the economic argument for SMRs strongly informs the future of compact fusion. Indeed, it is important to investigate the economics of compact fusion now, as key technological advancements highlighted here may yet result in the realization of compact fusion before large-scale fusion (on the ITER pathway).

Ultimately, studies on the commercialization of fission SMRs may smooth the entry for economical compact fusion technology, and thus both communities should consider the shared benefits of prospective crossover economic studies. Certainly, any future fusion economic study should draw parallels with, and capture methods and information from the wealth of fission SMR studies available [6, 16, 18], as well as any future real in-service SMR experience. Early observations of the potential economic benefits of compact fusion are made in the "smaller, sooner" and "faster fusion" philosophies as presented in [2], [4] and [19].

Regulation and Safety in Compact Nuclear

The indirect costs associated with regulation and safety are attributable for driving up the cost of nuclear [8, 17], but the extent to which these issues are problematic for a future fusion industry are yet unknown. A new licensing framework is already being drawn up for the future fleet of fission SMRs, but little exists for fusion, other than information from the ITER licensing process. Whilst safety focus across the nuclear industry has historically increased cost, it has also contributed towards the creation of a safety culture, in which nuclear safety is considered paramount [8]. Safety culture is intrinsically tied into the development fission SMRs, where the recognition that safety is critical is factored into SMR designs from the start of development [5, 8]. Looking ahead, it is a priority that this strong platform of nuclear safety culture percolates into the future fusion industry, even though the risks associated with the two technologies are somewhat different.

It is important to note, that though unforeseen regulatory hurdles lay ahead in the commercialization of fusion, the principal reason that safety issues are not considered in great depth is because the near-term technological challenges are more critical to the overall success of fusion. Though the regulatory process for fusion is understandably seen as a future issue, and though the challenges involved remain inherently different to fission, monitoring and learning from the current nuclear and future SMR regulatory environments may allow for a smoother process in licensing future fusion power plants.

Societal Challenges for the Future of Nuclear

Crucial to the success of compact nuclear technologies, more generally, is public acceptance. Unfortunately, public discourse surrounding nuclear technology inevitably focuses on major incidents like Chernobyl and Fukushima. Following the Fukushima incident, there was public outcry against nuclear leading to shutdown of reactors around the globe, though in countries such as the UK public attitudes to nuclear remained relatively unchanged [20]. Thus, even though per unit of power produced nuclear fission energy has stochastically lower risk than renewable energy, public perception remains a hidden cost to the industry [21]. Furthermore, despite efforts to distance itself from its own past, the stigma attached to nuclear also appears to influence public attitudes towards fusion [22]. The primary message is that there is a need to improve communication with the public to facilitate understanding to increase acceptance, to ultimately preserve research funding. Both communities must reconcile and avoid making further false promises, such as Lewis Strauss' "*electricity too cheap to meter*", and the long-standing quip that "*fusion is always 30 years away*". An honest account of both technologies is necessary on all aspects, good or bad.

Encouragingly, active improvements are being sought in the fission community, with several nuclear-positive initiatives born out of the realization that there is a need to inform the public and change perception of nuclear power (see *Environmental Progress, Generation Atomic and 5MinuteNuclear.org*). The compact fusion community has an opportunity to be open about the challenges that lie ahead, and should be open about the hazards associated with the production of 14MeV neutrons from D-T fusion, the quantities and types of radioactive waste produced, and information about the problems associated with use of tritium. If not openly addressed now, such issues could prove problematic for the perception of fusion in the future.

A Bright Nuclear Future

Both compact nuclear technologies sit in a strong position to provide the world with safe and affordable energy for the future. In general, nuclear power can contribute worldwide in providing a source of baseload electricity generation thereby reducing the dependency on fossil fuels, slowing global warming and improving air quality [23, 24]. However, compact nuclear is also uniquely capable of providing energy to isolated areas with little or no grid infrastructure, and it also has potential for co-generation. In the coming decades, there will be a great need for widespread desalination to significantly improve the global standard of living, particularly in developing nations, as well as an ever-growing need to decarbonize industrial energy use, including transportation [25]. Compact nuclear can address both: through surplus electricity generation, and small-scale, localized production of process heat for industrial applications [16, 24, 26].

Perhaps most exciting is the potential for future compact nuclear technology to work functionally with renewables, by balancing the grid through load-following, an issue large-scale nuclear reactors today cannot solve [7, 24, 27]. Thus, a compact nuclear future can complement, secure and improve a renewable energy future, and that alone is a very attractive proposition indeed.

ENDNOTES

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