Emerging Nuclear Reactor Technologies
For Mid-Term Commercial Deployment

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Introduction

ENERGY security, sustainability and affordability are key challenges confronting global energy policy. 2050 electricity demand is expected to increase by a minimum of 27% compared to 2010 [1]. In 2012, 437 nuclear fission reactors generated 10.3% of the world's electricity. A further 67 reactors were under construction [2], more than at any point since 1988 [1]. Nuclear energy will play a crucial role in the low-carbon energy mix.

Nuclear energy systems are split into four generations of technology (figure 1). Gen IV technology has four goals; to improve the sustainability, economics, safety performance and proliferation resistance of nuclear energy systems [3]. The Generation IV International Forum (GIF) was established in 2001 to coordinate the research required to realise next generation reactor designs [3]. Six key emerging technologies are highlighted by the GIF [3]. A brief overview of the technology and a summary of research progress is given in this paper.

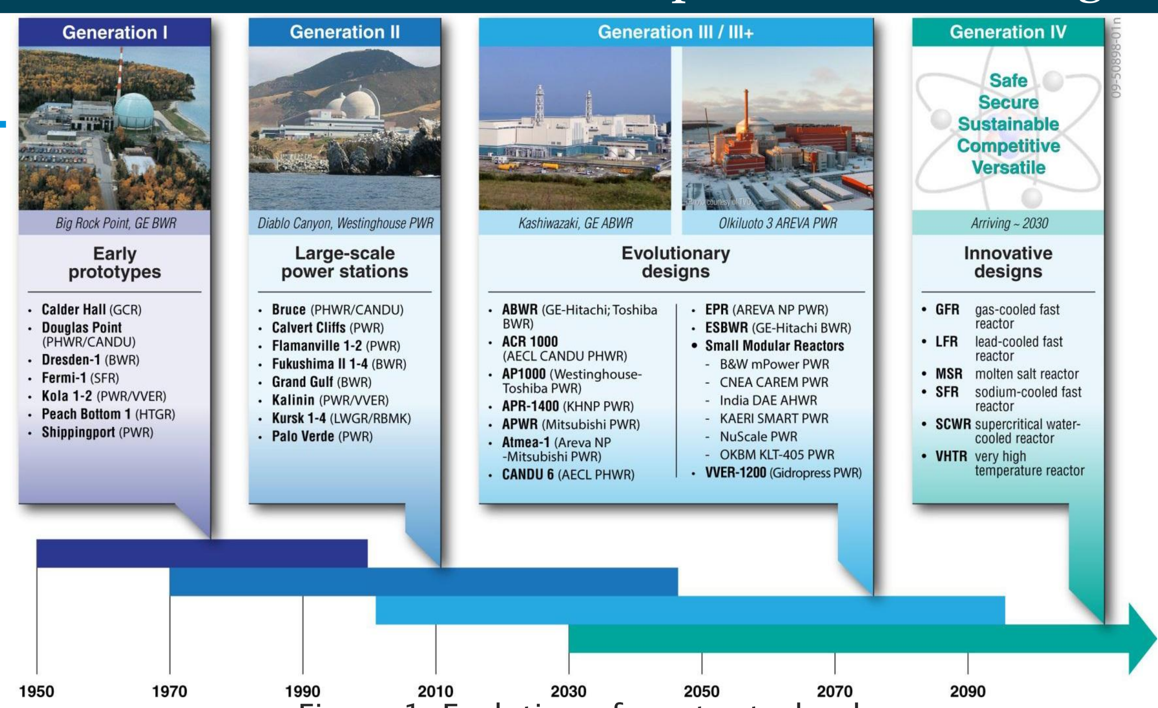

Figure 1: Evolution of reactor technology

Sodium Cooled Fast Reactors (SFR)

SFRs are one of the most mature Gen IV technologies [4] with worldwide investment already exceeding US $50billion [5]. By utilising fast spectrum neutrons and closed fuel recycling, SFRs present significant improvements in fuel utilisation and are one of the nearer term options for managing plutonium and minor actinide waste [6].

Current research activities focus on preparing the system for commercial deployment. This includes developing under sodium inspection techniques, aggregating worldwide operating experience and demonstrating actinide management on a commercial scale [6].

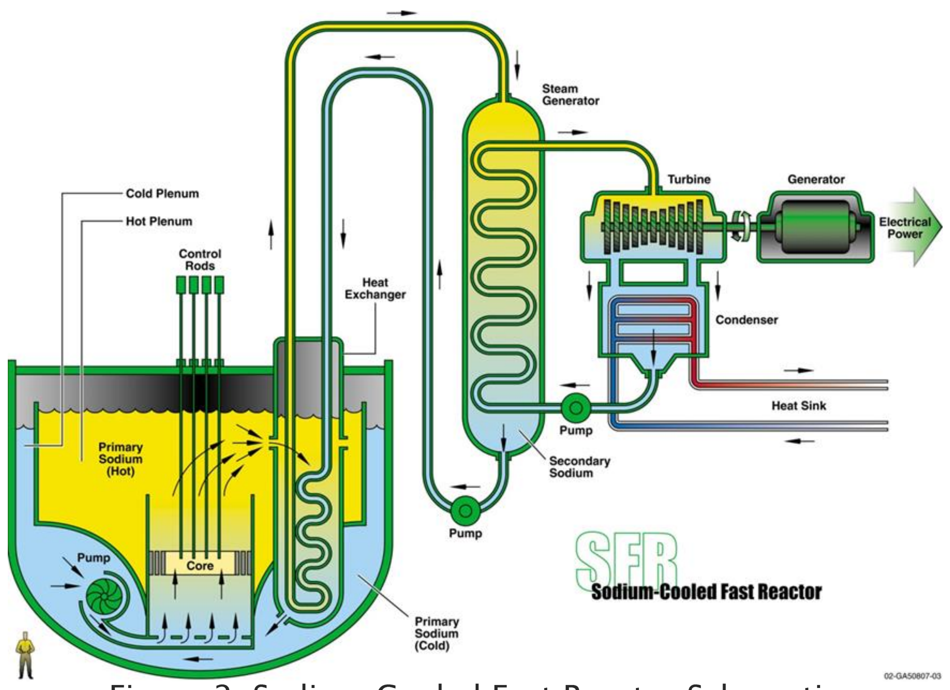

Figure 2: Sodium Cooled Fast Reactor Schematic

Very High Temperature Reactor (VHTR)

The VHTR is a helium gas cooled, graphite moderated reactor planned for an open fuel cycle [4]. The main purpose of this reactor is to achieve extremely high core outlet temperatures of over 1000ºC [3] as opposed to 320ºC for current LWRs. The increased core outlet temperature improves the thermodynamic efficiency of the system. More importantly, the high outlet temperature increases the potential for co-generation. Temperatures in excess of 750ºC are required for hydrogen production. Hydrogen could partially replace hydrocarbons as the energy vector of choice, and the VHTR presents one of the few low-carbon ways of making hydrogen in significant quantities. Research focusses on designing fuel and materials that can withstand the extremely high temperatures.

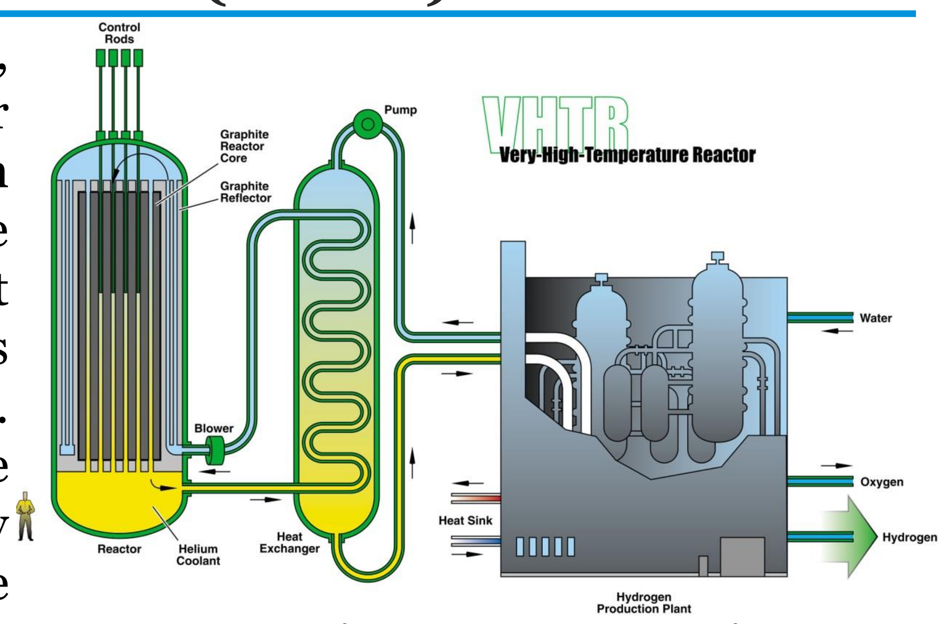

Figure 3: Very High Temperature Reactor Schematic

Gas Cooled Fast Reactor (GFR)

The GFR is another gas cooled, high temperature design. A helium coolant is used but no moderator is required due to the use of the fast neutron spectrum. This allows the use of a closed fuel cycle for full actinide management and the use of both fissile and fertile fuels. This is expected to deliver fuel efficiencies two orders of magnitude greater than current LWR designs [3]. It will operate at similar temperatures to the VHTR of around 850ºC, which provides similar opportunities for cogeneration. Since there are many shared challenges with the VHTR, it is likely the GFR will be an evolution of the VHTR.

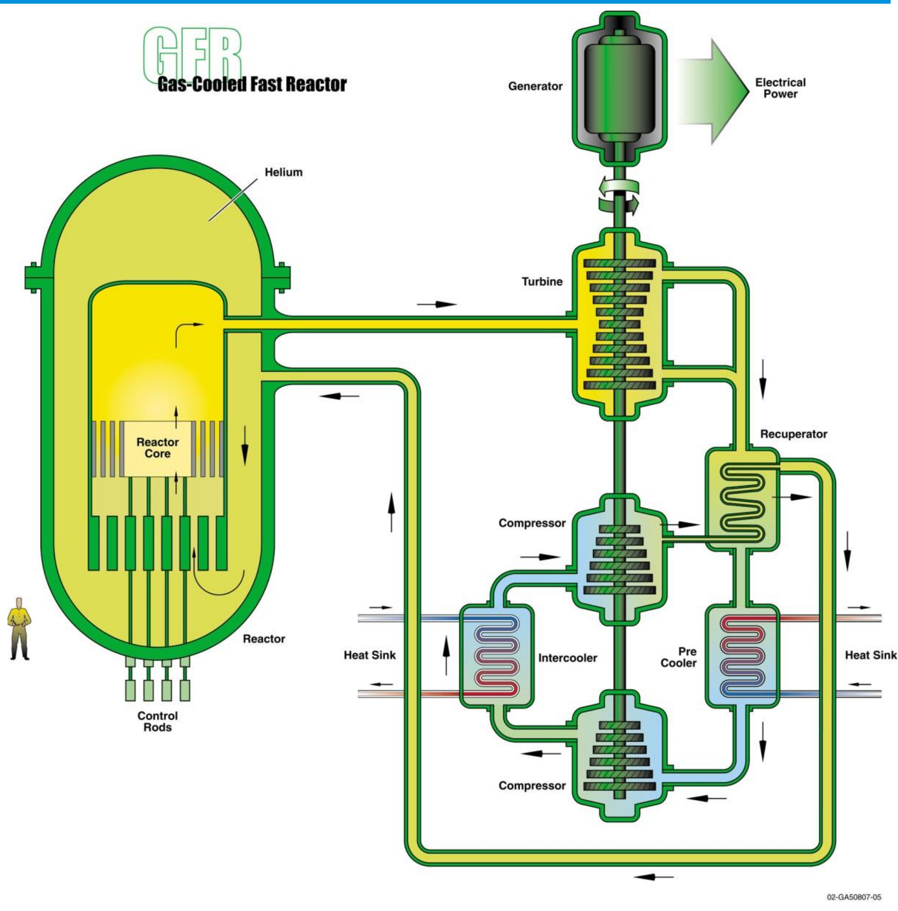

Figure 4: The Gas Cooled Fast Reactor Schematic

Supercritical Water Cooled Reactor (SCWR)

The main design aim of the SCWR is to increase the efficiency of current LWR reactor designs by operating at high temperatures and pressures, above the thermodynamic critical point of water [3]. The SCWR concept has been inspired by state-of-the-art coal-fired power stations that have successfully increased net efficiency while decreasing the capital cost required per unit electricity. Due to the single phase coolant, the primary loop is vastly simplified. This results in estimated savings of 50% in specific capital cost. The SCWR design has never been built, significantly delaying the deployment for demonstration purposes [6]. Extreme materials are required to withstand the high temperatures and pressures, radiation and the highly corrosive environment due to supercritical water [6].

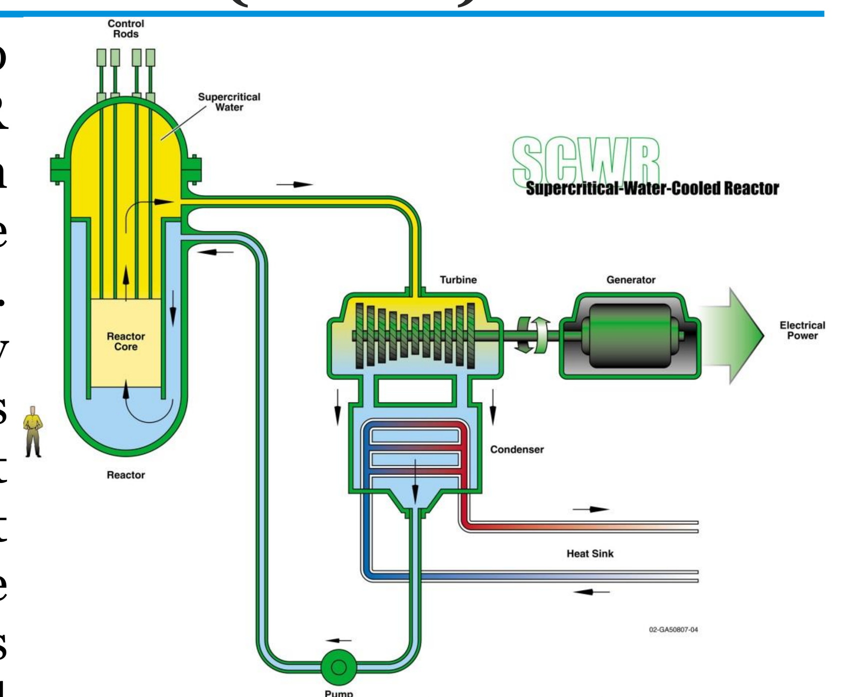

Figure 5: Super Critical Water Cooled Reactor

Lead Cooled Fast Reactor (LFR)

The LFR refers to a fast reactor design cooled by lead or a lead-bismuth eutectic [5]. Both coolants are high temperature, low-pressure, chemically inert and feature good thermodynamic properties [6]. Using a fast reactor with a closed fuel cycle means the LFR can be used as a burner to consume minor actinide waste or as a breeder using thorium matrices [6]. The high melting point of lead requires the system to be maintained at a high temperature during maintenance to prevent solidification [6]. Lead is opaque, a property shared with sodium, and requires the development of advanced viewing techniques [6]. The natural toxicity of lead can pose issues [5].

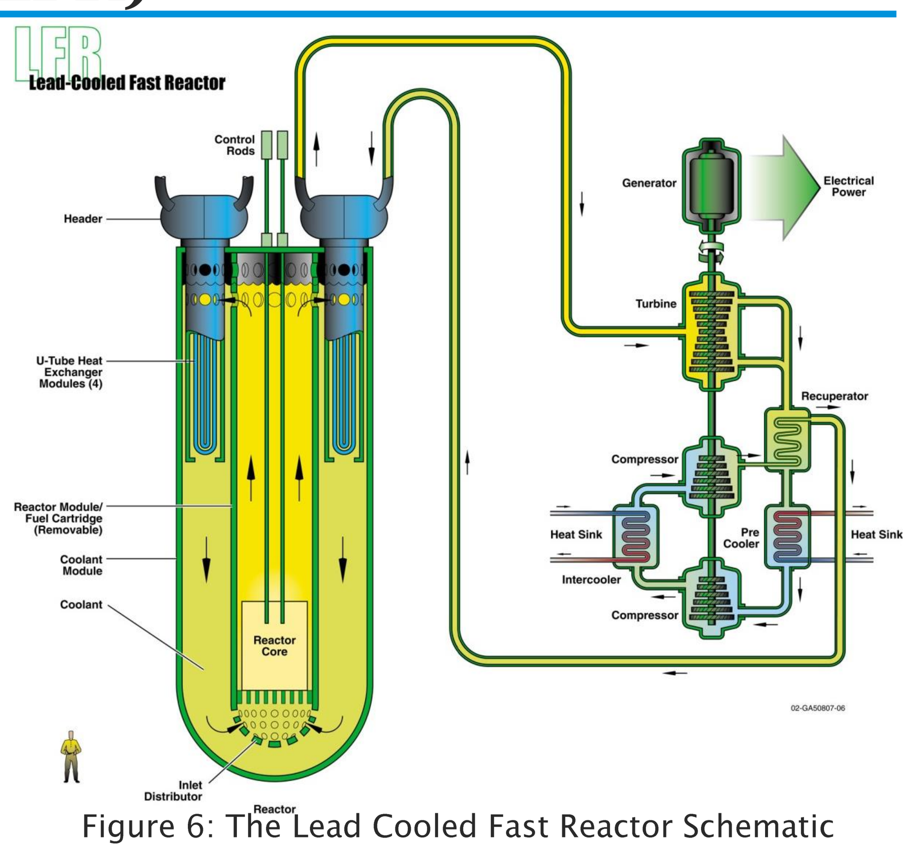

Figure 6: The Lead Cooled Fast Reactor Schematic

Molten Salt Reactor (MSR)

The uniquity of the MSR is that the fuel is dissolved in a molten mixture of fluoride salts [3]. The advantages of this innovative fuel design is the elimination of fuel fabrication. This vastly reduces fuel cycle costs [10]. It allows the adoption of a number of fuel cycles from burning LWR waste to breeding fissile ^{233}U from thorium [6]. The coolant is optically transparent allowing traditional viewing techniques to be employed [9]. The use of liquid fuel poses some Challenges. The development of a reprocessing strategy for a coolant/fuel mix remains a significant challenge to the deployment of this technology. Demonstration reactors are not expected to be deployed until 2040 [7].

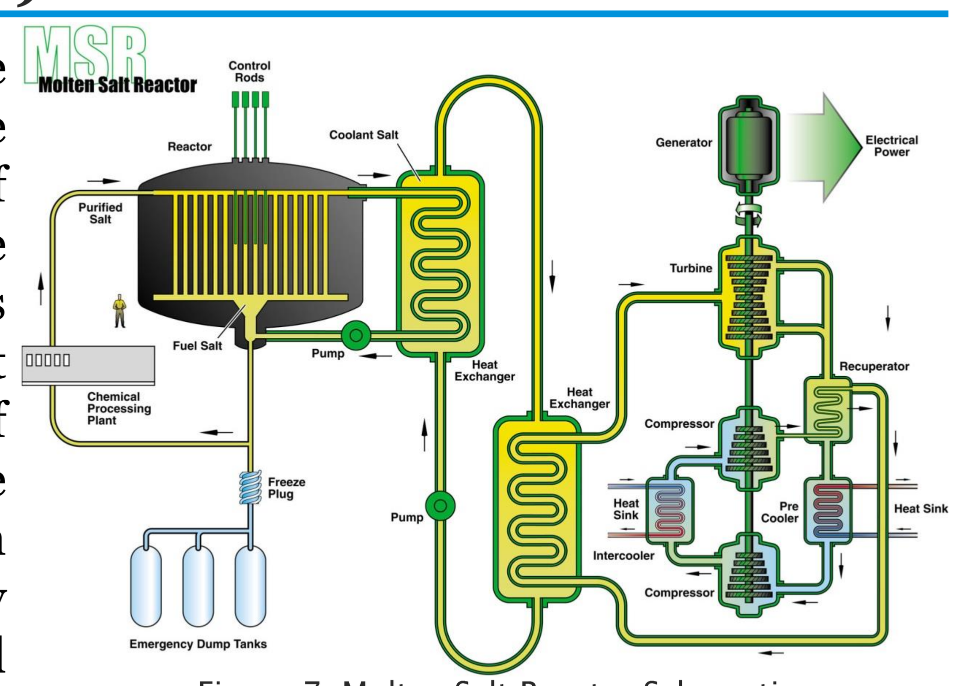

Figure 7: Molten Salt Reactor Schematic

Conclusions

The UK nuclear R&D partnership National Nuclear Laboratory has reviewed the six Gen IV reactor technologies against a set of metrics relevant in a UK context. Factors considered include safety, economics and technology readiness. This type of analysis has limitations. Efforts have been made to remove subjective bias from the analysis by incorporating reviewers' comments. Additionally, there has been no effort to weight the metrics in order of importance. The values given in table 1 should be used only as a basis for general comparison. The analysis shows a clear preference for the VHTR, while the SFR, LFR and MSR are all approximately comparable to current LWR technology. Fast reactor technology has advantages in terms of fuel sustainability and waste minimisation, but suffer in the analysis due to technological feasibility. The SFR is the most proven fast reactor design and it could be argued that this system is the most technologically feasible of all the fast reactors. The VHTR benefits from a wide network of support within the GIF, partly due to the prospect of commercial scale hydrogen production. This combined with operating prototype reactors in China and Japan makes the VHTR a prime candidate for deployment in the near future.

Technology	Score
SFR	68
VHTR	80
GFR	59
SCWR	54
LFR	65
MSR	65
LWR	68

Table 1: Gen IV technology multi-attribute utility analysis results, higher is better. LWRs shown for comparison [8].

References:
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