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ScienceDirect

Energy Procedia 160 (2019) 459–466

Energy Procedia

www.elsevier.com/locate/procedia

2nd International Conference on Energy and Power, ICEP2018, 13–15 December 2018, Sydney, Australia

A review on the development of nuclear power reactors

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Abstract

Nuclear power can solve the energy trilemma of supplying baseload, clean and affordable power. However, a review of nuclear power plant (NPP) builds show mixed results, with delays in Finland and in the US offset by successes in China, South Korea and the UAE. In the West, financing for new builds has been difficult in the face of a deregulated energy market, billion-dollar upfront investments, long build times and in the case of the US historically low gas prices. We explore how the nuclear industry is innovating in facing these challenges through a review of nuclear power developments in the past, present and future. Early developments in nuclear power in the 1950s resulted in a variety of designs, out of which the pressurised water reactor (PWR) became dominant for its compactness and overall economy. Over the next 10 years, several PWR-based small modular reactor (SMR) designs are expected to come online within an eight-year timeframe. Their modular construction and fabrication in a controlled factory setting aims to shorten build times from 8 to 3 years. However, the lack of established regulatory approval pathways may be a time-limiting challenge that needs to be overcome by the first fleet of SMRs. The passive safety and a smaller fuel loading of SMRs will allow them to be deployed at more potential sites, including brownfield replacements of old coal-fired power plants or power unconventional, remote or islanded grids. Some SMRs are also designed to load follow which will allow them to work harmoniously with intermittent renewables sources with the promise of an affordable, truly carbon-neutral grid. In the longer term, advanced nuclear reactors in the form of sodium cooled, molten salt cooled, and high temperature gas cooled reactors hold the promise of providing efficient electricity production, industrial heat for heavy industry as well as the generation of hydrogen for synthetic fuel.

Keywords: Nuclear power; baseload; dispatchable; carbon-free; uranium; Gen-4; small modular reactors.

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10.1016/j.egypro.2019.02.193

1. Current Nuclear Power

There are currently 454 nuclear power reactors supplying more than 10% of the world's electricity, operating at a high capacity factor of 81% (2017 world average). 31 countries operate nuclear power plants (NPP) with 70% of the world's nuclear electricity generated in five countries – USA, France, China, Russia and South Korea. Today, the average age of the operational power reactors stands at 30 years with over 60% of all NPPs having operated for more than 31 years [1]. The global nuclear fleet is dominated by Pressurised Water Reactors (PWRs) with 301 units comprising 66% of all NPPs in operation [2], followed by Boiling Water Reactors (BWRs) at 16% with 72 units, Pressurised Heavy Water Reactors at 11% with 49 units, Graphite-moderated Water-cooled Reactors (RBMKs) at 3% with 15 units in Russia, Gas Cooled Reactors (GCRs) at 3% with 14 units in the UK and two Sodium fast Neutron Reactors (SFRs) at 1% operating in Russia. Currently, 54 power reactors are under construction, the bulk of which are concentrated in Asia (figure 1) and one third of all reactors under construction are in China. NPP builds are also underway in the West, but in more modest numbers as the industry revives its nuclear supply chain left dormant from the slow rate of build over the last 20 years.

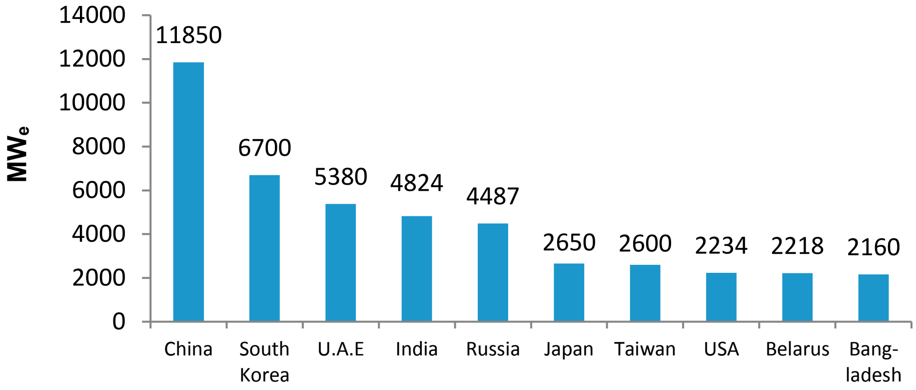

Fig. 1. Total net capacity of nuclear power under construction [3]

1.1. PWRs and BWRs

At the advent of the nuclear age, leading countries invested heavily in nuclear power, creating various indigenous designs: The Pressurised Water Reactor was first created for the US Navy to power maritime platforms (Nautilus, 1955) and later deployed on land for electricity generation (Shippingport, 1958). The PWR, which heats water to about 320°C at 150 atmospheres, is characterised by two separate coolant loops connected by a heat exchanger (HX), also known as a steam generator (figure 2).

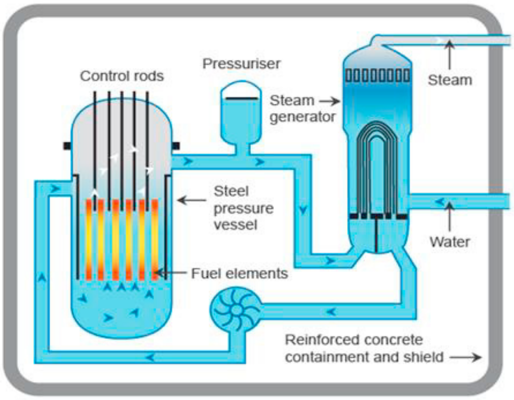

Fig. 2. Diagrammatic layout of the Pressurised Water Reactor [3]

Heat generated in fuel elements by splitting the atom (i.e. nuclear fission) is transferred to the HX to create steam that powers a turbine. Later, Argonne National Laboratory and General Electric (USA) developed the Boiling Water Reactor (Dresden 1, 1960), a kind of simplified PWR with a single coolant loop. The Boiling Water Reactor (BWR) operates at a lower pressure of 70 atmospheres to allow direct steam generation in the core at about 285°C. Both PWRs and BWRs use normal light water for cooling and neutron moderation (whereby neutrons are slowed to become more easily captured by the uranium fuel, resulting in fission) and thus are collectively known as Light-Water-Reactors (LWRs). LWRs use fuel in the form of uranium dioxide pellets where the fissile Uranium-235 content is 'enriched' from 0.7% (in its natural state) to about 4%. The enrichment is necessary as light water is neutron absorbing and thus the fissile content must be increased (per unit volume) to balance the loss of neutrons by water and material absorption. The remaining 96% U-238 content is also useful: Around 2% of the U-238 in the fuel bundle will transmutate into plutonium 239 and plutonium 240 after neutron capture. The plutonium is then 'burnt' in situ with the U-235 fuel, generating 40% of the total power. So to a significant extent, even uranium reactors create and burn their own fuel.

On average 2.43 neutrons are created for every fissioned uranium atom and these neutrons propagate to fission other uranium atoms in what is known as a chain reaction. In a power reactor the chain reaction is controlled by using burnable poisons (i.e. neutron absorbing material such as boron) and neutron absorbing control rods (CRs) that are moved into, or out of, the reactor core to control the neutron population and hence the exponential rate of change of reactor power. Adjusting control rod position maintains either a steady reactor power or initiates shutdown by a full insertion of the CRs.

Both PWRs and BWRs are intrinsically safe during operation, due to the fuel and moderator expanding at higher temperatures. Material expansion leads to less fuel & moderator per volume and thus a passive reduction in power. This characteristic is known as the "negative-temperature reactor coefficient". After a reactor is shut down, the fission products left over from burnt fuel still generate what is known as 'decay-heat' which at 1 hour after shutdown is about 1.2% of the heat generated when the reactor is at power. Thus for a 1000 $MW_{electric}$ reactor producing 3000 MW of heat, the decay heat is about 36 MW_{th}. Even though 36 MW_{th} is only a fraction of nominal thermal power, it is still substantial and requires either active cooling (driven by pumps) or passive cooling (driven by natural circulation). In the two major NPP accidents in the West: Three Mile Island (1979) and Fukushima (2011), both accidents were due to insufficient decay heat removal after reactor-shutdown. To improve the safety of reactors, new LWRs incorporate active and passive safety systems to manage the consequences of loss-of-flow accidents in the case of prolonged station-blackout event as seen in Fukushima.

1.2. Other Reactor Types

Without the benefit of enrichment technology, Canada originally developed the CANDU (Canada Deuterium Uranium) reactor to specifically use natural uranium. This is possible as heavy water is much less neutron absorbing than light water and reactor criticality could be maintained without fuel enrichment. Today, most CANDU reactors operate with slightly enriched fuel to improve fuel utilisation. Canada runs a CANDU-only fleet of NPPs concentrated in the state of Ontario. There is currently a plant refurbishment program underway to extend the life of these plants for another 30 years [4].

The UK, also took the route of using natural uranium as fuel but selected graphite for neutron moderation and carbon dioxide for cooling. This configuration was used for the Magnox Reactors (now retired) and the Advanced Gas Reactors (AGRs) of which fourteen are still operating. However, the UK is transitioning to a LWR fleet, having one PWR in operation (Sizewell B, Suffolk) and multiple LWR projects to follow.

The Russian graphite-moderated-light-water-cooled-reactors known as RBMKs (Reaktor Bolshoy Moshchnosty Kanalny or "High Power Channel-type Reactor") were also designed to use natural uranium. However, the RBMK had the undesirable characteristic of positive-void co-efficient, meaning that if water boiled away in the coolant channels, the neutron population would increase resulting in higher reactor power. This characteristic, together with graphite-tipped control rods (which temporarily increased neutron moderation during the act of reactor shutdown) contributed to the Chernobyl accident in 1986. It's important to note that no RBMKs were built in the West and that those still operating have been substantially modified with International advice for improved safety. Finally the

Russian operate two Sodium Fast Reactors (SFRs) one of which is tasked with destroying old weapons-grade plutonium stockpiles.

2. History of NPP builds

Nuclear energy production releases no CO_2, however the initial build out of NPPs was motivated by the desire for energy security. In reaction to the sharp rise in oil prices in 1973, France built 55 PWRs in the space of 16 years (1977–1993). In the US NPP numbers peaked at 111 units in 1991 [5] with 95 GW coming online between 1970 and 1990.

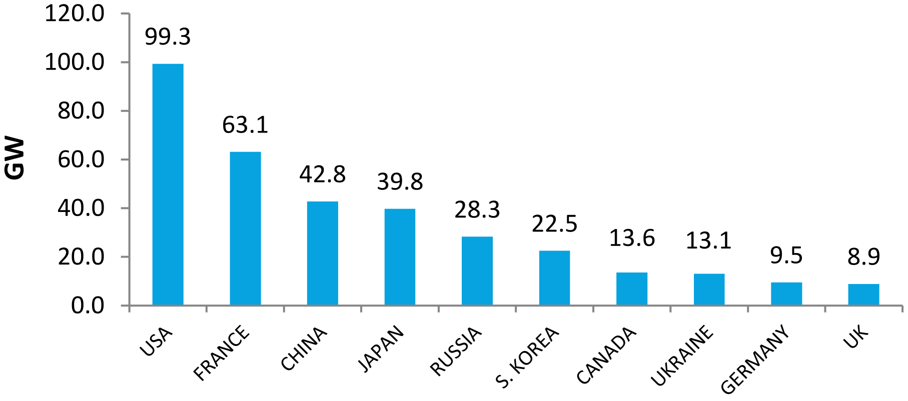

Fig. 3. NPP installed capacity (PRIS, Oct. 2018)

Currently there are 98 units (99 GWe capacity) in operation in the US, followed by France with 58 units (63 GWe capacity) then China with 46 units (43 GWe capacity, figure 3). China is quickly expanding its nuclear capacity, having overtaken Japan for third place in 2017. Taken as a whole, Europe operates more NPPs than the US with 130 units.

NPP construction-starts in the US peaked at 44 units in 1976 and began to slow in late 1970s for a variety of factors *"including slowing electric demand growth, high capital and construction costs, and public opposition. Costs, schedules, and public acceptance were all influenced by the accident at the Three Mile Island plant in 1979."* This pattern was repeated elsewhere, with new reactor builds continuing to decline after Chernobyl (1986) before recovering briefly before the Fukushima accident in 2011 (Figure 4).

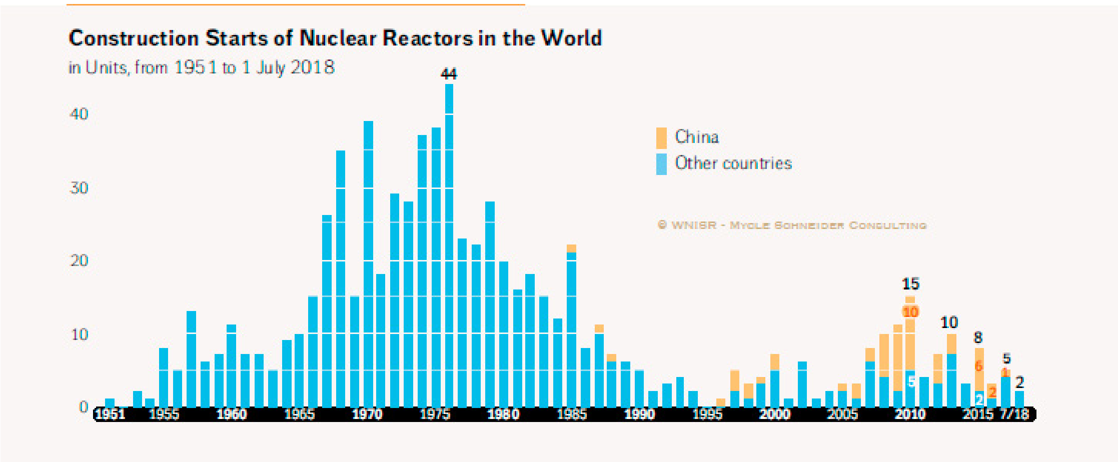

Fig. 4. Construction starts of NPPs in the World and in China. [1]

After the Fukushima NPP accident, many governments initiated reviews of NPP operations, safety, management and procedures. All NPPs in Japan were shut down pending regulatory review. As of November 2018, 9 NPPs have restarted in Japan after satisfying new regulatory safety standards [6]. In China, the 5 year build targets set by the State Council were slowed and new reactor build applications were suspended pending review. China's ban on new nuclear projects was lifted in Nov 2014, about three and a half years after the accident. China resumed NPP build outs in the 13th 5 year plan (2016-2020) calling for the doubling of nuclear capacity from 27 GWe to 58 GWe [7]. Currently, China's nuclear capacity is 42.8 GWe with 10.8 GWe under construction. In the US, the Blue Ribbon Commission on America's Nuclear Future recommended the National Academy of Sciences (NAS) conduct an assessment of lessons learned from the accident [8]. This led to more thorough reviews of NPP Beyond Design Basis Accident scenarios, improved safety culture in NPP operations and tightened coordination between the Office of Nuclear Security and Incident Response (part of NRC) with other Federal, State, and local emergency response units.

2.1. NPP builds today

Today, NPPs constructions have shifted from the West to the East with 4 out of 5 reactors under construction based in Asia and Eastern Europe. Between 2011 and 2018, 48 new reactors were grid-connected of which 29 units assumed operations in China. In the period 2016-2017, electricity generation from nuclear increased slightly by 1% to 2503 TWh. Most of the increase was attributed to three new NPPs commissioned in China, lifting the country's nuclear power generation by 18% and expanding the share of nuclear electricity from 3.6% to 3.9% of total domestic production. [1]

Currently, there are 54 reactors under construction led by China with 11 reactors, India 7, Russia 6, South Korea 5 and the UAE with 4 units. Countries with 2 reactors under construction include Bangladesh, Belarus, Japan, Pakistan, Slovakia, Ukraine and the USA. Argentina, Brazil, Finland, France and Turkey all have 1 reactor under construction.

Today's global nuclear installed capacity stands at 400 GWe. However, 169 GWe of that nuclear capacity will need replacing by 2030 to maintain the status quo in global nuclear capacity [1]. This could be sustained by the continued build-out of NPPs in Asia, Eastern Europe and the Middle East but recent delays in nuclear builds in Olkiluoto (Finland), Flamanville (France) and Georgia (USA) makes large NPP build-outs in the West less likely. Instead, the West could diversify NPP builds with small modular reactor (SMR) and non-LWR reactor (i.e. High Temperature Gas Reactors - HTGRs, Molten Salt Reactors - MSRs etc.) deployments.

3. Small Modular Reactors

In the face of delays in 1GW reactor builds in the West, it has become clear NPP vendors must innovate to build tomorrow's reactors faster, using safer, simplified designs. The general idea is to move construction away from the plant site and onto a factory mass-production line to decrease build costs and increase build quality. Shortening build times is financially beneficial because 80% of the NPP life-cycle costs are incurred during the initial build phase. Thus, any year-long delay(s) in reactor construction could dramatically increase the reactor financing cost (i.e. interest repayments).

Small modular reactors are loosely classed as reactors with a power output of 300 $MW_{electric}$ or less and can encompass both LWR and non-LWR designs. Though for the next 10 years, nearly all deployable SMRs will be of the LWR variety which have accumulated 50+ years of operational experience and thus are easier to license compared to non-LWR designs. The root of SMR development could be traced back to the start of the nuclear age but the first real effort to design a compact and integral-PWR (iPWR) was in the International Reactor Innovative and Secure (IRIS) program. The IRIS program, led by Westinghouse, sought to fit the separate parts of reactor core, heat exchangers, control rods and pressurizer into a single, compact module. Findings from the IRIS program (1997 - 2009) led to the US DOE (Department of Energy) funding two competing i-PWR designs at USD 226 million each. BWXT received one grant to develop the mPower SMR (160 MW_e) and NuScale the other to develop the NuScale Reactor (60 MW_e) [9]. Today, the mPower project has been mothballed but NuScale is on track to build a first-of-a-kind (FOAK) 12-unit-plant supplying 720 MW_e at Idaho National Laboratory (INL). The Nuclear Regulatory Commission (NRC) is currently reviewing NuScale's design certification which is scheduled to be completed in 2020. Construction will then start with a projected finish date of 2026.

Other SMR projects within an 8 year deployment time frame include the Argentine CAREM (32 MW_e); South Korean SMART (100 MW_e + desalination as bonus), the Chinese ACP-100 (100 MW_e) from CNNC and the Russian KLT-40S with two barge-mounted 35 MW_e units, one of which was loaded with fuel in November 2018.

All of the aforementioned SMR designs have large water reservoirs supplying passive cooling to safely remove fission-product decay heat after the reactor is shutdown. Passive cooling uses natural buoyancy forces to drive the less dense (and thus lighter) hot water from the core up through a 'riser', removing the need for pumps for 'active cooling' post shutdown. The buoyant flow passes through the DRACS (direct reactor auxiliary cooling system) which removes the decay heat thus becoming cooler before being recirculated back through the core. This eliminates the type of 'station blackout' accidents seen in Fukushima.

By having smaller power outputs, SMR units can switch on and off in small power increments in response to the intermittent supply and demand on the grid [10]. As an example, NuScale has investigated the load flowing characteristics of an SMR with a 57 MWe windfarm in Idaho using historical wind data [11]. Other SMR applications include providing high-reliability power for mission-critical infrastructure, black-start capability for micro-grids and steam generation for district heating and desalination [12]. Factory fabrication of modular components aims to reduce build times from 8 years to 3 years and the smaller size would mean a lower initial capital outlay, making SMRs accessible to more countries.

The IAEA (International Atomic Energy Agency) is currently establishing SMR deployment guidelines, noting SMRs are especially suited to new-to-nuclear countries, many of which are facing the retirement of aging coal fired power plants. The smaller size and enhanced safety of SMRs means the traditional EPZ (Emergency Planning Zone) around large 1 GW reactors can shrink from a 10 mile (16 km) radius to the site boundary, making SMRs ideal brownfield replacements for retiring coal-fired power plants.

4. The Future of Advanced Reactors

Research is underway on a variety of advanced reactors, including sodium-cooled fast neutron reactors (SFRs), lead-cooled fast reactors (LFRs), molten salt reactors (MSRs) and high temperature gas reactors (HTGRs). As previously mentioned, Russia already have 2 SFRs in operations which can produce more fuel than it burns or destroy long-lived radioactive waste. This versatility stems from sodium having an extremely low neutron capture cross section resulting in a surplus of neutrons in the core that can be used to either burn actinide waste or bred more fissile fuel. Sodium is also a very good thermal conductor which enhances passive heat removal after reactor shutdown. China is constructing its own pilot SFR (600MW_e) that is scheduled for commissioning in 2023 in Xiapu. In contrast, UK, USA, France and Japan have shut down their older experimental SFRs, though research in SFRs is continuing in France [13]. Apart from the SFR, Russia is developing a lead cooled fast reactor (BREST-300) [14,15]. Using lead as coolant is safer than using sodium (which is more chemically reactive) even though lead is not as neutron-efficient. To compensate for the higher neutron absorption of lead, uranium-nitride fuel with a higher uranium loading per unit volume is planned for use in LFRs.

Molten Salt Reactors can fulfil a variety of missions including fuel breeding and high-temperature operations for supplying industrial heat. The Chinese Government is investing USD 3.3 billion to build the first liquid-fuel MSR prototype since the MSR experiment at Oak Ridge National Laboratory in 1965-1969. Successful demonstration of the LF-1 demonstrator could pave the way for a MSR Breeder using thorium-232 as the fertile material for breeding uranium-233 fuel. Terrestrial Energy in Canada is pursuing a simplified design that uses denatured (i.e. low enrichment) uranium, and Terrapower and Elysium Industries in the US are researching a molten chloride-salt fast reactor to burn the US spent-fuel inventory accumulated from LWR operation. Many other reactor-vendor startups are also working on MSR designs with much pre-licensing activity occurring in Canada.

High Temperature Gas Reactors (HTGRs) have been understudy for over 50 years. The first helium-cooled, graphite moderated HTGR operated at Peach Bottom, USA from 1966 to 1974. The helium coolant is inert, single phase and has no reactivity feedback; while the large graphite core gives the reactor superior thermal inertia which absorbs the decay heat after shutdown, making HTGRs passively safe. HTGRs, like MSRs have very high temperature outputs from 750°C to 1000°C allowing the supply of industrial heat without CO_2 emissions. Later this year, China is set to commission an experimental air-cooled high-temperature gas reactor (HTR-PM) which uses two reactor modules (500 MW_{th}) to supply a common turbine outputting 200 MW_e.[16] Successful demonstration of the HTR-PM will lead to the development of HTR-PM600 outputting 600 MW_e of power [17]. HTGRs are suited for inland deployment where water may be scarce for LWR cooling.

5. Summary

Nuclear power has grown quickly in the 1970's and 1980's reaching a global installed capacity of 400 GWe today. In an increasingly carbon constrained future, nuclear power is becoming recognized as an integral part of the world's low-carbon energy solution. New builds in nuclear power has been most successful with State support as seen in China and South Korea, with China on track to double its nuclear power capacity from 27 GWe to 54 GWe by 2020. Some studies project Chinese nuclear power capacity to expand to as much as 500 GWe should China aim to arrest global temperature rise to 1.5°C [18]. Canada is also reinvesting in nuclear power, having announced a $12 Billion program to refurbish 4 CANDU reactors as well as announcing a $1.2 B program to retrofit Canadian Nuclear Laboratory at Chalk River in readiness for siting the first non-PWR based SMR. In the near term, NuScale is on track to build an FOAK PWR-based SMR in Idaho National Labs by 2026 in an effort to reduce build times, enhance safety and reduce build costs. Despite the resurgence in interest in NPPs, it is tempered by the fact that 169 GWe of nuclear capacity is scheduled to come offline between 2020 and 2030 should no new reactor life-extension be granted. Whether State-backed 1 GW_e nuclear reactors and commercially financed SMRs could cover the retirement of older NPPs remains to be seen.

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