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Review Article

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Advanced Reactor Concept (ARC) A Nuclear Energy Perspective

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ABSTRACT

Due to climate change on earth, governments are pursuing the policy of gradually reducing Greenhouse Effects. For example, country like Germany has an aim to reduce greenhouse gas emissions by 40% by 2030. However, they are also intent on shutting down nuclear power stations. This means that coal fired power stations are now working harder to make up the shortfall, and greenhouse gas emissions are on the rise. The intended increase in renewable energy generation is far too slow to compensate. Last year, coal burning was at its highest level in more than 20 years and with global rise of population, the demand for electricity also is on ascending curve correspondingly, yet if we arguably, consider that nuclear energy is a source of renewable energy, then is it fear to say that nuclear energy as a source of clean energy must sustain its existence. However, the question is how we can assure their operational safety and guarantee that the new generation as an advanced Small Modular Reactors (aSMRs) can deliver such a promise. This short review examines the advanced Generation IV (GEN-IV) in form of Advanced Reactor Concept (ARC) may be able achieve such high bar goal both from proliferation and non- proliferation point of view and reduces threat of any radiation leak based nuclear accident that we have encountered past few decades.

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Introduction

Energy policies are implemented throughout the energy production, distribution and consumption chain, the main strategies include

- access to new energy resources,
- extra production from existing resources and, increasing efficiency, and
- Improving consumption efficiency and reducing losses in distribution through transformation.

Demand for electricity is continuously on sharp rise annually, given growth of industrial front and population globally. The move by countries like Germany to give up their nuclear fleet certainly is no help for reducing the crisis of global warming effect due to impact of and rise of carbon in our environment surrounding us.

As a matter of the deployment of new clean energy sources and infrastructure around source of renewable energy should be the main priority goal among manufacturing companies that are playing in energy sector. They must begin immediately and continue for the foreseeable future to meet the carbon-reduction objectives and expand worldwide access to reliable and affordable energy in the form of either renewable or non-renewable infrastructures.

Global Warming and unusually rapid increase in Earth's average surface temperature over the past century primarily due to the greenhouse gases released as people burn fossil fuels (Figure-1).

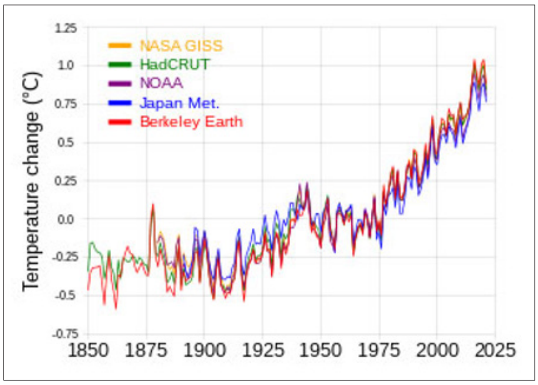

Figure 1: Global Average Temperature Change

The recent news in March of 2022) was indicating that ice in North Pole (Arctic) is on an accelerating path of melting down due to global warming and rise in earth temperature and as a result a chunk of ice at the size of Los Angles dropped into ocean water of Arctic and it will continue to melt over the years to come.

In fact, on March 22, 2022. Arctic sea ice has likely reached its maximum extent for the year, at 14.88 million square kilometers (5.75 million square miles) on February 25 of same year [1]. Figure-2

Considering all the serious concerns about global warming and greenhouse effects, the energy companies should be in quest a better source of producing energy as source of generating electricity to meet the demand for it on annual basis as we stated in above, while reducing the gas carbonic, which is on constant rise and move by countries like Germany away from nuclear is certainly not a pattern in right direction, as matter of fact, as Elon Musk of Tesla the pioneer of battery driven car, once said: "Shutting down of nuclear plants is a total madness". Even folks like him are in need of electricity to charge the batteries of their cars at some charging stations.

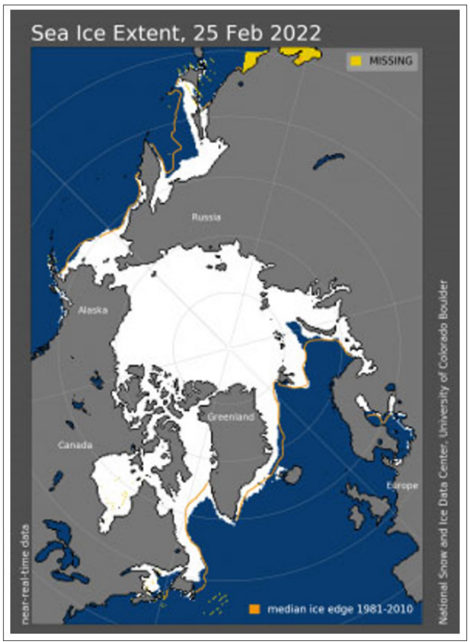

Figure 2: Arctica Ice Melting Progress

However, if we just rely on renewable source of energy such as Wind or Solar powers to charge all of these battery driven cars will not be sufficient enough at their charging stations, if some day we manage to replace all gas guzzler cars that we own today and driving on the road around the globe presently.

Why Nuclear Power Plant Energy

The major growth in electricity production industries in the last 30 years has centered on the expansion of natural gas power plants based on gas turbine cycles. The most popular extension of the simple Brayton gas turbine has been the combined cycle power plant with the Air-Brayton cycle serving as the topping cycle and the Steam-Rankine cycle serving as the bottoming cycle for new generation of nuclear power plants that are known as GEN-IV. The Air-Brayton cycle is an open-air cycle and the Steam-Rankine cycle is a closed cycle. The air-Brayton cycle for a natural gas driven power plant must be an open cycle, where the air is drawn in from the environment and exhausted with the products of combustion to the environment. This technique is suggested as an innovative approach to GEN-IV nuclear power plants in form and type of Small Modular Reactors (SMRs) and now as part of Advanced Small Modular Reactors (aSMRs) that also Advance Reactor Concept (ARC) falls under that technology. The hot exhaust from the Air-Brayton cycle passes through a Heat Recovery Steam Generator (HSRG) prior to exhausting to the environment in a combined cycle. The HRSG serves the same purpose as a boiler for the conventional Steam-Rankine cycle [2-4].

In 2007 gas turbine combined cycle plants had a total capacity of 800 GW and represented 20% of the installed capacity worldwide. They have far exceeded the installed capacity of nuclear plants, though in the late 90's they had less than 5% of the installed capacity worldwide. There are number of reasons for this. First natural gas is abundant and cheap. Second combined cycle plants achieve the greatest efficiency of any thermal plant. And third, they require the least amount of waste heat cooling water of any thermal plant.

A typical gas turbine plant consists of a compressor, combustion chamber, turbine, and an electrical generator. A combined cycle plant takes the exhaust from the turbine and runs it through a Heat Recovery Steam Generator (HRSG) before exhausting to the local environment.

The HRSG serves the function of the boiler for a typical closed cycle steam plant. The steam plant consists of a steam turbine, a condenser, a water pump, an evaporator (boiler), and an electrical generator. In a combined cycle plant, the gas turbine and steam turbine can be on the same shaft to eliminate the need for one of the electrical generators.

However, the two shafts, of two generator systems provide a great deal more flexibility at a slightly higher cost. In addition to the closed loop for the steam, an open loop circulating water system is required to extract the waste heat from the condenser. The waste heat extracted by this 'circulating' water system is significantly less per megawatt for a combined cycle system as the open Brayton cycle exhausts its waste heat directly to the air.

The layout for the components of a typical combined cycle power plant is given below in Figure-3.

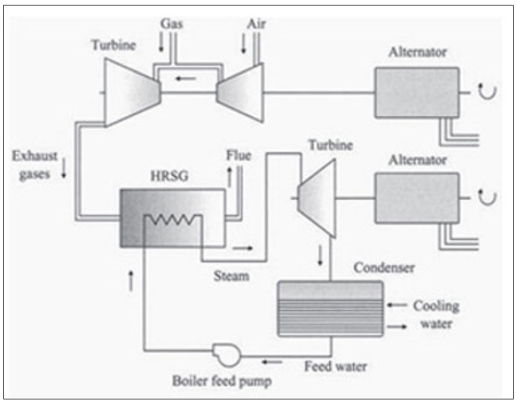

Figure 3: Typical Gas Turbine Combined Cycle Power Plant

General Electric (GE) currently markets a system that will produce 61% efficiency at design power and better than 60% efficiency up to 87% of design power for gas turbine combined cycle plants [4].

Advanced Reactor Concept

ARC Clean Energy SMR development is based on key issues associated with nuclear energy – safety, economics, proliferation, and suitability for distributed energy networks Advanced reactor types where as it Provides Low Development Risk. Several advantages of this type of reactors are followed as below:

- **Nuclear security and nonproliferation (a key motivation for ARC)** – ARC100 has-20-years core life without access to fueling.
- **Safety** – Self protecting against all anticipated-transients-

without-scram including station blackout and uncontrolled single-rod withdrawal.

- **Fuel cycle and waste management** – Flexible options: once through with onsite cask storage, proven technology for fuel treatment and recycle.
- **Economics** - Factory production and modular construction.
- **Economic return** - Load following capability compatible with solar and wind distributed grids, use of waste heat and off-peak power applications.
- **Low development risk** – Mature, advanced and demonstrated technology foundation such as Experimental Breeder Reactor-II (EBR-II).

We all know that the future role of advanced nuclear energy depends on companies providing solutions to energy that are timely and economically competitive business from manufacturing point of view for these advanced nuclear reactor under the umbrella of Advanced Reactor Concept (ARC), thus companies must create competitive advantages for the development of advanced small modular reactors throughout their supply chain, which includes all from reactor construction contracts and fuel supply to Spent Nuclear Fuel (SNF) and waste management techniques.

More than 70 projects are underway under development in 17 countries that are expected to be more cost-effective to build and operate. Developing advanced Small Modular Reactor (aSMR) of Generation IV (GEN-IV) and research continues to go in different path and methodology of technology base on using the Tristructural Isotropic [TRISO] ceramic-coated fuel configuration packaged in a graphite matrix, as depicted in Figure-4, and we are engaging a concept called functional containment.

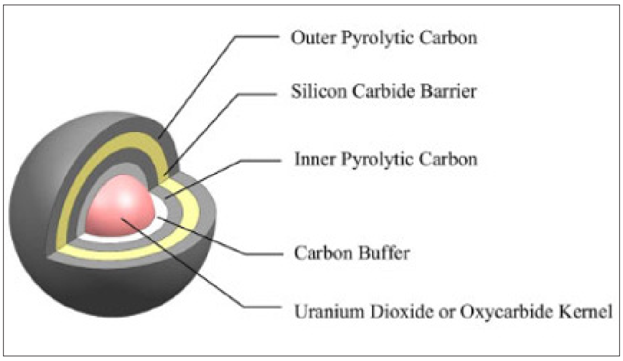

Figure 4: TRISO Coated Particle Fuel

Moreover, Each TRISO particle consists of a Uranium, Carbon and Oxygen fuel kernel, which is encapsulated in three layers of Carbon and Ceramic-based coating that prevents radioactive fission products from being released and that is also in support of non-proliferation concept behind this generation of ARC technology of GEN-IV.

Furthermore, radionuclides contained within those tri-structural isotropic coatings, specifically the silicon carbide coating, enables us to do a couple of things. One is to get of the larger containment structures. Secondly, it allows us to shrink the emergency planning zone because the mechanistic source term is greatly reduced. And it improves the safety case, because the fuel is able to go to much higher temperatures and continue to retain those radionuclides. Thus, we have gotten multiple benefits that come starting at the kernel and the particle level of the fuel design, from safety and non-proliferation point of these new generation of Nuclear Power Plants (NPPs).

The Safety factor of these ARC driven as an aspect of aSMR generation has fully taken under consideration the approach of Probabilistic Risk Assessment (PRA) for their actual operation with idea of 24 x 7 x 360 and their lifecycle period.

Note that: Probabilistic Risk Assessment (PRA) is a tool that has gained increasing popularity across several industries from nuclear power to human spaceflight to systematically and comprehensively evaluate risks associated with complex engineered facilities.

Among the newly ARC technological approach that can come to our attention immediately and supposedly will be in operation is Canadian Brunswick ARC-100. The mission of this reactor is to commercialize a disruptive new technology for power generation in the form of an advanced small modular nuclear reactor. The reactor will produce 100 MWe of energy, be factory-built and offer the customer fixed fuel costs for 20+ years.

The ARC-100 nuclear reactor as depicted in Figure-5, can be used for distributed power, incremental capacity additions due to its modularity capability, load following, and base load applications. Additionally, because of its size (i.e., Figure-6), dispatch flexibility and robust safety features, the ARC reactor will be an attractive option for non-traditional uses, such as water desalination, shale oil extraction and hydrogen production.

As we stated, the non-proliferation features of the ARC-100 make it suitable for deployment anywhere in the world. The reactor's design creates a "walk away" passive safety system that ensures the reactor will never melt down even in a disaster that causes a complete loss of power to the plant site. The ARC-100 has Large Operating Safety Margins as like as Ambient pressure primary system, No potential for H2 generation, Small temperature rise in metallic fuel and make the reactor No need for offsite or emergency AC power systems. Moreover, the 20-year fueling cycle based on new fueling concept of TRISO, gives the customer a high level of energy security, while outsourcing the complexity of fueling operation.

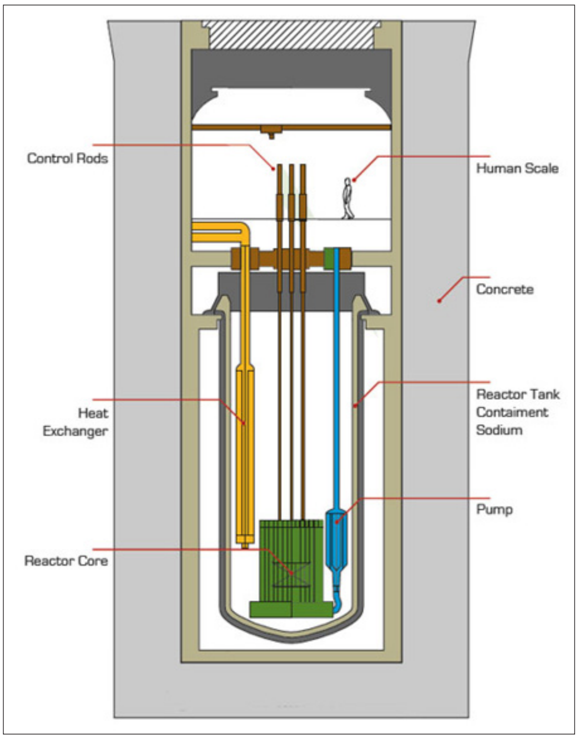

Figure 5: Artistic View of ARC-100

With its efficient use of resources and self-incineration of nuclear waste, the ARC reactor fully supports the sustainable development goals of countries and markets that might not otherwise have any effective options.

The ARC-100 is based on technology proven by over 30 years of successful operation of the Experimental Breeder Reactor (EBR-II), an experimental program operated by the Department of Energy (DOE) of U.S. government. The basic EBR-II technology has been enhanced by ARC through numerous, significant proprietary innovations (for which patents have been granted and applied) to create a "Fourth Generation" solution that will have wide applicability in both the US and export markets around the world.

The ARC-100 Nuclear Fuel Cycle of, due to its "breeding concept", will be well compatible with the "reactor-fuel cycle" network, especially the advanced fuel cycles, so that a suitable combination of GEN-IV advanced reactors, including based light water, Heavy water, liquid metal, molten salt designs with different fuel cycles will be able to increase the lifespan of current nuclear fuel resources by pursuing "Wait & See" policy to manage Spent Nuclear Fuel and use them on the network.

Advanced Reactor Types

The Department of Energy Office of Nuclear Energy (NE) and its national laboratories support research and development on a wide range of new advanced reactor technologies, such as advanced Small Modular Reactor (aSMR) and their new concepts known as Advanced Reactor Concept (ARC) to help meet the nation's energy, environmental, and national security needs, while also delivering their operational safety in virtue recently disaster nuclear accident such as Fukushima Japan (2014) as natural accident less than decade ago and that was the turning point for countries such as Germany to turn back to nuclear energy as source of electricity to meet their demand for such life saver as means of production for much needed electricity current and trying to coal and other means of renewable source of energy [5].

Advanced reactor types as illustrated in Figure-7 are listed as:

• Advanced Small Modular Water-Cooled Reactor

Small Modular Reactor (SMR) uses water as a coolant (i.e., NuScale) and is smaller than traditional Light Water Reactor (LWR). Most SMRs based on light water technologies have the appropriate Technology Readiness Level (TRL) for commercialization in the near-term

• Liquid Metal-Cooled Fast Reactor

This type of reactor uses metal sodium or lead (a preferred option), or lead/bismuth eutectic (i.e., Natrium™ TerraPower (TP)/General Electric Hitachi (GEH) as a coolant instead of water, allowing the coolant to operate at higher temperatures and lower pressure than current reactors.

The LMFR may be operated as a breeder, a burner of actinides from spent fuel, using inert matrix fuel, or a burner/breeder using thorium matrices.

• Molten Salt Reactor

This type of reactor uses molten fluoride or chloride salts as coolant.

MSR concepts, which may be used as efficient burners of transuranic elements from spent light-water reactor (LWR) fuel, also have a breeding capability in any kind of neutron spectrum ranging from thermal (with a thorium fuel cycle) to fast (with a uranium-plutonium fuel cycle). Whether configured for burning or breeding, MSRs have considerable promise for the minimization of radiotoxic nuclear waste.

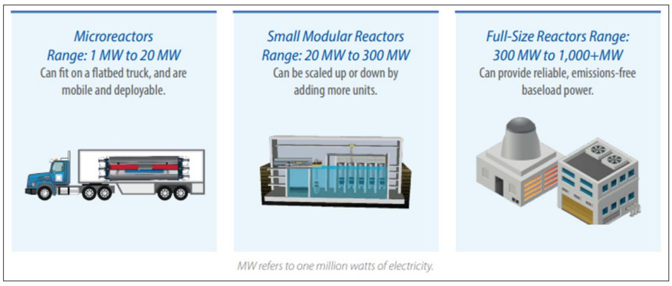

Figure 6: Advanced Reactor Sizes

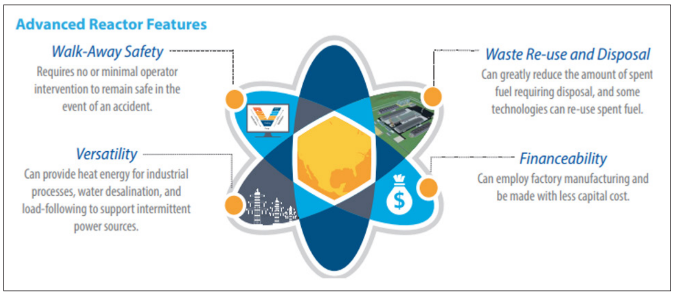

Figure 7: Advanced Reactor Features

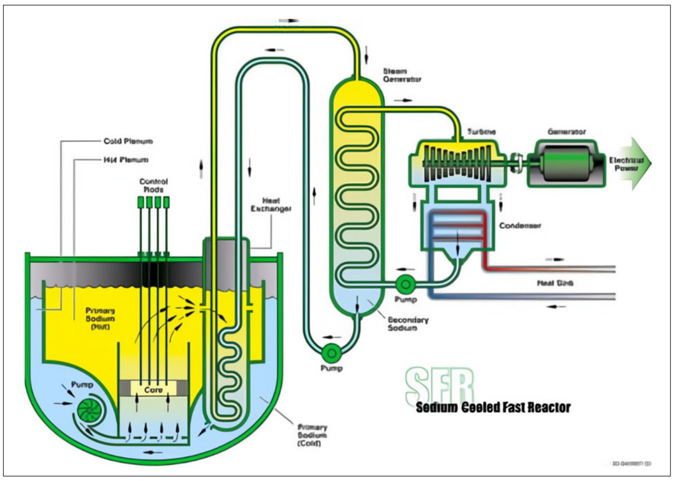

Figure 8: ARC Nuclear, New Brunswick Power (NP) to Cooperate on SMR Development

Conclusion

The Advanced Reactor Concepts (ARC) program, an expanded version of the Generation IV research, development and demonstration (RD&D) program, sponsors research, development and deployment activities leading to further safety, technical, economical, and environmental advancements of innovative nuclear energy technologies. The Office of Nuclear Energy (NE) will pursue these advancements through RD&D activities at the Department of Energy (DOE) national laboratories and U.S. universities, as well as through collaboration with nuclear industry and international partners. These activities will focus on advancing scientific understanding of these technologies, establishing an international network of user facilities for nuclear RD&D, improving economic competitiveness, and reducing the technical and regulatory uncertainties for deploying new nuclear reactor technologies.

In conclusion, we may state that one of next big future for Advanced Reactor Concept (ARC) is the concept of ARC-100

Mwe modular reactor targeted for operation in 2029 in New Brunswick Canada and they agreed to work cooperatively to explore the development, licensing and construction of an advance Small Modular Reactor (aSMR) based on ARC Nuclear's mature Generation IV (GEN-IV) Sodium-cooled Fast Reactor (SFR) as illustrated in Figure-8.

The ARC-100 offers 100 megawatts of electricity, enough to support 250, 000 people as Advanced Small Modular Reactor (aSMR) concept [5].

Advanced Small Modular Reactors (aSMRs) as a way to provide safe, clean, and affordable nuclear power options. The advanced SMRs currently under development in the U.S. represent a variety of sizes, technology options and deployment scenarios. These advanced reactors, envisioned to vary in size from a couple megawatts up to hundreds of megawatts can be used for power generation, process heat, desalination, or other industrial uses. They offer multiple advantages, such as relatively small size, reduced capital investment, location flexibility, and provisions for incremental power additions. SMRs also offer distinct safeguards, security and nonproliferation advantages. The authors present a thorough examination of the technology and defend methods by which the new generation of nuclear power plants known as GEN-IV can safely be used as an efficient source of renewable energy.

The Government of New Brunswick earlier this year announced CAD$20 million (USD16 million) in funding towards the advancement of the ARC-100 sodium-cooled fast reactor. The Government of Canada has also this year announced funding to advance the design of Moltex's Stable Salt Reactor – Wasteburner and WAste to Stable Salt (WATSS) facility, and has also announced funding for NB Power to prepare the Point Lepreau site for SMR deployment and demonstration, and to the University of New Brunswick to expand its capacity to support SMR technology development.

The ARC-100 is a 100 MWe fast reactor that leverages proven technology developed at the Experimental Breeder Reactor-II (EBR II) sodium-cooled fast-reactor, which was developed at the US government's Argonne National Laboratory (ANL) where it operated successfully for thirty years.

The timeline for ARC-100 commercialization has been "accelerating", Labbe said. The first – Scoping – phase was completed in 2019; the second phase – Preliminary Design, which includes the second VDR phase, the completion of preliminary design work, validation of cost estimates and integrated schedule, as well as scoping fuel supply and manufacturing capabilities – is now under way and is expected to be completed by the end of 2023. Phase 3, which will include completion of the detailed engineering, procurement orders, construction permit licensing and approval, site preparation work and the execution of a construction contract, is scheduled to run until 2026.

The final – deployment – phase will run from 2027-2030, according to the timeline, and the company expects the first core to be delivered on site by the end of 2028

A simple, inherently safe design, operating at atmospheric pressure, yields lower plant cost. The following points are benefit of ARC-100 once goes to production and they are listed as:

✓ SODIUM AS COOLANT
The use of sodium instead of water as the coolant allows the reactor to operate at lower pressures, improving the efficiency and safety of the system.

✓ RECYCLING WASTE
The ARC-100 consumes its own waste and recycles its own fuel, leaving almost no long-term waste. In addition, the technology can recycle waste from traditional reactors to generate energy.

✓ MALL SIZE
The total plant size is less than a city block and its modularized components can be shipped and installed at the site using regular

commercial equipment, such as barges, rail, trucks, and construction cranes.

✓ PASSIVE SAFETY
With a system that is "walk away" fail safe, the ARC-100 does not depend on extra pumps or operator intervention in the event electric power to the plant is disrupted.

✓ TWENTY YEAR REFUELING CYCLE
The proprietary core of the ARC-100 is designed to operate for 20+ years without refueling.

✓ METAL FUEL
The ARC-100 uses a metallic uranium alloy fuel, which is much simpler and cheaper to fabricate than oxide fuel with exceptional heat transfer characteristics.

Technical feature of ARC-100 is summarized as:
- Sodium-cooled fast reactor.
- 286 MWt, 100 Mwe.
- Sodium 355 °C/510 0C.
- Metallic uranium alloy fuel.
- Long 20-year fuel cycle / 60-year life.
- Low pressure pool-type reactor.
- Inherent safety performance.
- No need for emergency generators.
- Superheated steam cycle.

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