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Current trends in Mobile Nuclear Reactor's (MNRs): A Review

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ABSTRACT

The IAEA Department of Nuclear Energy continues to facilitate endeavours of Member States in the development and deployment of mobile nuclear reactors (MNRs), acknowledging their potential as a viable solution to meet energy supply security, both in newcomer and expanding countries interested in MNRs. In this regards, balanced and objective information on technology status and development trends for advanced reactor lines and their applications are reviewed through published reports and other technical documents. The driving forces in the development of MNRs are their specific characteristics. MNRs show the promise of significant cost reduction through modularization and factory construction which should further improve the construction schedule and reduce costs. In the area of wider applicability MNRs designs and sizes are better suited for partial or dedicated use in non-electrical applications such as providing heat for industrial processes, hydrogen production or sea-water desalination. About 43 published studies (1967-2017) are reviewed in this paper. It is marked from the literature survey articles that they can be deployed incrementally to closely match increasing energy demand resulting in a moderate financial commitment for countries or regions with smaller electricity grids.

1. Introduction

Energy is a scalar quantity of a central concept in science. Energy can exist in many different forms and all forms of energy are either kinetic or potential. The energy associated with motion is called kinetic energy. The energy associated with position is called potential energy. The energy is a measurable, transmissible, and transformable condition, whose presence causes a substance to tend to change its state in one or more respects [36]. Nowadays, the whole worlds are totally dependent on an abundant supply of energy for living and working and this is the crucial components in all

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sectors of modern economics (European Commission). The importance of energy is it provides the heat and electricity to the industry, transport and many other facilities in daily life. Residential uses of energy are the most basic uses of energy. They account for almost forty percent of total energy use globally. Commercial uses of energy include the power used by the companies and business throughout cities and lighting of commercial buildings and spaces. Transportation is fully dependent on energy. The transport sector includes all vehicles and over 70 percent of petroleum used goes to into the transport sector [15].

According to World Energy Outlook from the OECD's International Energy Agency (IEA), electricity demand is increasing twice as fast as overall energy use and is likely to rise by more than two-thirds 2011 to 2035 in the world. In 2012, 42% of primary energy used was converted into electricity. While the increased in electricity demand is most dramatic in Asia. Figure 1 below shows the world electricity consumption by region.

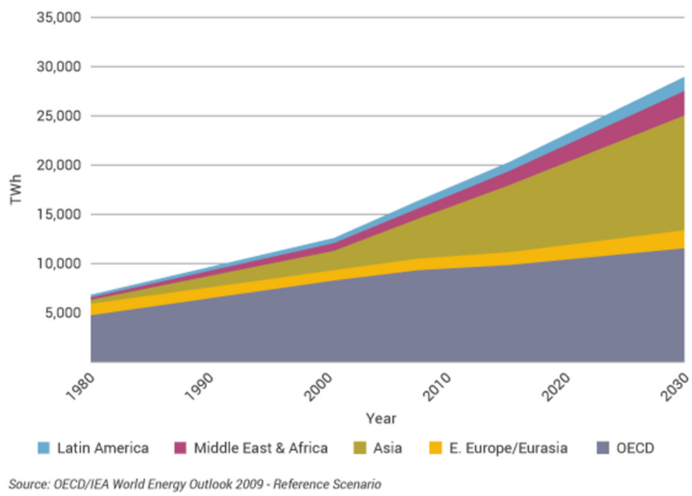

Fig. 1. World electricity consumption by region

With the United Nations predicting world population growth from 6.7 billion in 2011 to 8.7 billion by 2035, demand of energy must increase substantially over that period. Both population growth and increasing standards of living for many people in developing countries will cause strong growth in energy demand, as outlined in the chart above. However, some two billion people still have no access to electricity currently. It is a high priority to address this lack and a serious issue to be solved. The world will definitely need greatly increased energy supply in the future, especially the cleanly-generated electricity. To meet this electricity demand, all major international reports on energy future suggest an increasing role for nuclear power as an environmentally benign way of producing electricity on a large scale. Renewable energy sources such as solar and wind are costly per unit of output and are intermittent but can be helpful at the margin in providing clean power [38].

In electricity demand, the need for low-cost, continuous, reliable supply of energy sources is necessary. Nuclear energy is one of the best option. Actually, what is nuclear energy? Where exactly nuclear energy release from? In this case, we have to discuss the energy production from the atomic level. We all know that, everything around us is made up of tiny object called atoms. Most of the mass of atom are concentrated in the centre, which called nucleus. Proton and neutron are subatomic particle that comprises the nucleus. The nucleus of very large atom can split into two to produce the heat energy called fission. This happen when the daughter mass is difference with the mother mass to create energy. Fission is the energetic splitting of large atoms such as Uranium or Plutonium into two smaller atoms, called fission products. To split an atom, you have to hit it with a neutron. Several neutrons are also released which can go on to split other nearby atoms, producing a nuclear chain reaction of sustained energy release. This chain nuclear reaction is able to produce thermal energy in nuclear reactor, then is it transform in mechanical energy to turn the turbine, finally electrical energy to be used by the industry. There are number of characteristics of nuclear power which make it particularly valuable, which is its fuel is a low proportion of power cost, giving power price stability. Other than that, nuclear fuel is on site and not depending on continuous delivery. Also, it is dispatchable on demand, has a fairly quick ramp-up, contributes to clean air and has low-CO2 objectives. Lastly, it gives good voltage support for grid stability. These attributes are mostly not monetised in merchant markets, but have great value which is increasingly recognised where dependence on intermittent sources has grown, and governments address long-term reliability and security of supply [38]. Today, there are over 440 commercial nuclear power reactors operable in 31 countries, with over 390,000 MWe of total capacity. About 60 more reactors are under construction. Nuclear energy provides over 11% of the world's electricity as continuous, reliable base-load power, without carbon dioxide emissions. 55 countries operate a total of about 245 research reactors, and a further 180 nuclear reactors power some 140 ships and submarines [27].

Apart from the commercial nuclear power plant, mobile nuclear power plant is one of big milestone in nuclear technology. A mobile power plants is different the other nuclear reactor is that they are transportable, which means they can move from one spot to another. The mobile power plants usually were equipped to a truck of tracked vehicle, on one or more trailers, on a self-propelled chassis, or on a railroad flatcar. On a certain place, floating mobile power plants was introduced. The floating power plant may supply the energies for the coastal area. The power generate by the mobile power plants depends on the type of the primary motor and the rated horsepower of the motor and the dimension of the power plants equipment. The power also depends on the load-carrying capacity of the transport vehicle. The output power generally was ranged from 10 kW up to 150 kW [40]. The mobile power plant can be used as the following application:

- Emergency Power in Developing Nations
- Power for Oil Rigs/Mining/Industrial Operations
- Pad or Section Power
- Electric Motor Fracking
- Enhanced Oil Recovery Operations
- Distributed Generation or Micro-Grids
- Construction Sites/Bridging Power
- Special Events
- Temporary Power During Maintenance of Main Systems
- Emergency Power for Natural Disasters
- Electricity for Military Compounds in War Zones
- Electric Power for Seasonal Peak Demands
- Grid Stability and Support

Mobile nuclear power plants have many advantages as they can move from one location to another. Usually, when disaster did happen, the power supply is cut off due to failure of power system. Thus, mobile nuclear power plants create a backup supply for inadequate electricity to anywhere needed. The mobile nuclear power reactor can provide electricity event to area where it is difficult to access. Yet, the potential for movement of the reactor unit providing more protection from natural disaster (seismic or tsunami) or man-made (air crash) hazards [39]. The moveable nuclear power plant can also eliminate the need to set up a special site for its construction. Since the location also been simplified, it is unnecessary to bring out viability studies on the environment. Mobility of nuclear power reactor also creates a very low environmental impact and the dismantling can be done in a specialized site [30]. Moreover, with usage of nuclear as a fuel, there will be huge savings in forex and such savings can be used for important things like needed infrastructure that will benefit our people and our country [7].

In this project, design of a floating mobile nuclear power reactor for emergency power supply is proposed. Generally, the design concept is that, a small modular reactor (SMR) is mounted on a floating offshore platform similar to those used by oil and gas industry. Then, the platform can be towed to target spot to supply electricity. The extra advantage of using the platform is that, we can utilise the platform that are many abandoned in the ocean which can lead to sea pollution. The following part of this report will include the conceptual design, detailed engineering design and the economic management of the nuclear power plant.

2. Nuclear Technology

2.1 Progress of Nuclear Technology

In 1896, Henri Becquerel had discovered a new phenomenon which came to be called radioactivity. Then, he began investigating the phosphorescence in uranium salts together with Pierre Curie and Marie Currie [26]. Otto Hahn and Fritz Strassmann showed that the new lighter elements were barium and others which were about half the mass of uranium in Berlin, thereby demonstrating that atomic fission had occurred at the end of 1938. Lise Meitner and her nephew Otto Frisch then explained this by suggesting that the neutron was captured by the nucleus. This caused severe vibration leading to the nucleus splitting into two not quite equal parts. The calculated energy released from this fission was about 200 million electron volts. This figure was then experimentally confirmed by Frisch in January 1939 [4].

During World War II, multiple countries began programs of investigating the possibility of constructing an atomic bomb as a weapon which utilized fission reactions to generate far more energy than could be created with chemical explosives. The Manhattan Project of the United States with the help of the United Kingdom and Canada, developed multiple fission weapons which were used against Japan in 1945 at Hiroshima and Nagasaki. During the project, the first fission reactors were developed as well, though they were primarily for weapons manufacture and did not generate electricity. The design of a nuclear weapon is more complicated than it might seem. For example, a weapon must induce criticality for detonation after it hold one or more subcritical fissile masses stable for deployment. It also is quite difficult to ensure that such a chain reaction consumes a significant fraction of the fuel before the device flies apart, so it must be manufactured in a nuclear reactor [5]. In 1951, the first nuclear fission power plant was the first to produce electricity at the Experimental Breeder Reactor No. 1 (EBR-1), in Arco, Idaho [43].

Nowadays, nuclear technology was used as the source of electricity in many countries. Examples of reactor which commonly used are pressurized water reactor (PWR) and boiling water reactor (BWR). PWR and BWR are types of thermal neutron reactor design. Both are using light water as the moderator and coolant. BWR is much simpler design compared to PWR but the thermal efficiency can be higher because of its single loop design [39]. Other than that, nuclear technology also has been commercialised in industrial applications. Since some ionizing radiation can penetrate matter, they are used for a variety of measuring methods. For oil and gas exploration, nuclear well logging is used to help predict the commercial viability of new or existing wells. The use of a neutron or gammaray source and a radiation detector are involved in this technology, which are lowered into boreholes to determine the properties of the surrounding rock such as porosity and lithography. In industrial radiography, x-rays and gamma rays are used to make images of the inside of solid products, as a means of non–destructive testing and inspection [2].

For future technologies, more than a dozen advanced reactor designs are in various stages of development [40]. The Small, sealed, transportable, autonomous reactor (SSTAR) is one of the future technologies which being primarily researched and developed in the US, intended as a fast breeder reactor that is passively safe and could be remotely shut down in case the suspicion arises that it is being tampered with. For thorium-based reactors, it is possible to convert Thorium-232 into U-233 in reactors specially designed for the purpose. In this way, thorium, which is four times more abundant than uranium, can be used to breed U-233 nuclear fuel [16]. Nuclear reactor technology is actually has been under continuous development since the first commercial exploitation of civil nuclear power in the 1950s. This technological development is presented as a number of broad categories (generations), and each representing a significant technical advance compared with the previous generation [9].

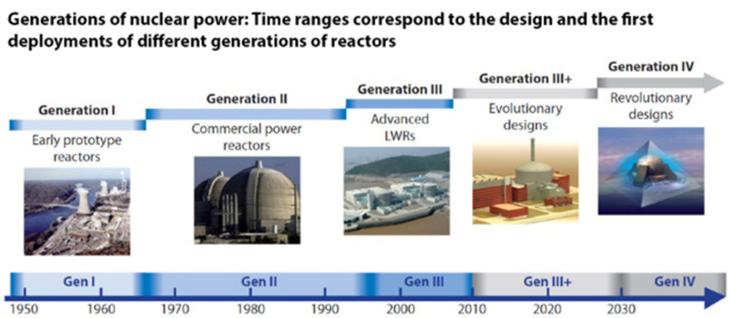

Fig. 2 Generation of Nuclear Technology

2.2 Types of Mobile Nuclear Reactors

One of the fascinating facts is that, scientists even make the nuclear power reactor to be transportable. A mobile nuclear power reactor is no longer a myth but a product that can be mass produced for mutual benefit of all human being. Review on existing or planned types of mobile nuclear power reactor will be included in the following section.

2.2.1 Akademik Lomonosov

This low-power floating nuclear power station is developed and designed by Russia. It has a length and width of 144 m and 30 m respectively. It can displace a weight of 21,500 ton and a crew of 70 people. This reactor can power up to 70 MWe or 300 MWt, with an efficiency about 23.33%. Apart from generating electric power, the Akademik Lomonosov can produce approximately 240,000 m^3 of clean and fresh water from sea water by using desalination technique. The construction of this reactor is approximately 12 years and it has a lifespan of 40 years. It has to be re-fuelled for every three years and the whole plant will be towed home and overhauled at the wharf for every 12 years to undergo service and maintenance. For the plant design, this reactor must have floating power unit that has been assembled completely with the use of an advance developed technology for constructing atomic ice breakers and navy ships. Certainly, the reactor needs onsite auxiliary facilities

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and lines for transmitting electricity and heat to the shore. The plant is mobile and can be stationed anywhere onshore and even on the beds of big rivers. Figure 3 shows conceptual image of Akademik Lomonosov, Afrikantov OKBM [19].

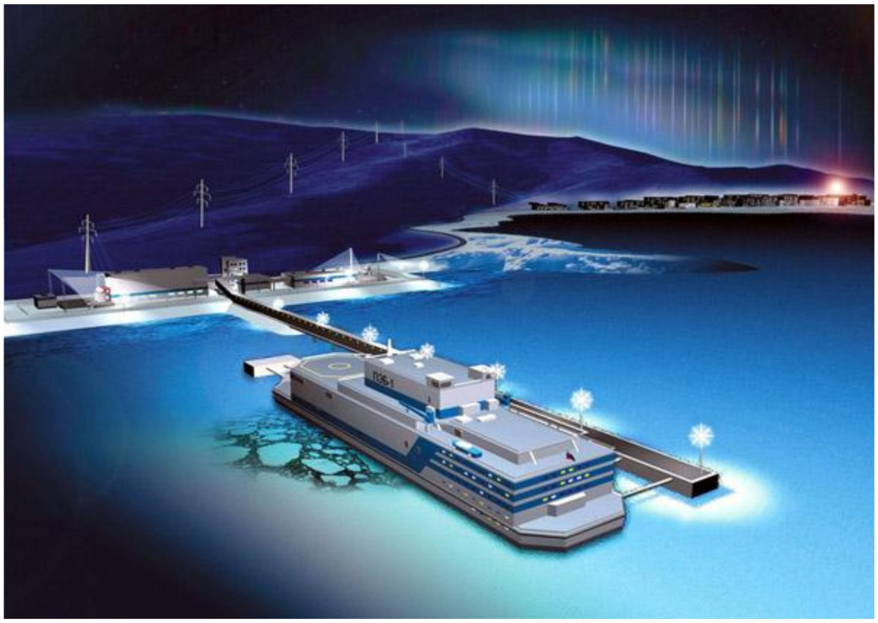

Fig. 3. Akademik Lomonosov, Afrikantov

2.2.2 Offshore Floating Nuclear Plant (OFNP)

Research group leads by Jacopo Buongiorno from Massachusetts Institute of Technology (MIT) is collaborated with researcher from the University of Wisconsin, Chicago Bridge and Iron Company, together proposed a reactor based on a spar-type floating platform with catenary mooring. This reactor has a low centre of gravity for hydrodynamic and static stability and can reduce the transmission of seismic impacts from the sea floor, tsunami, wave and wind impact.

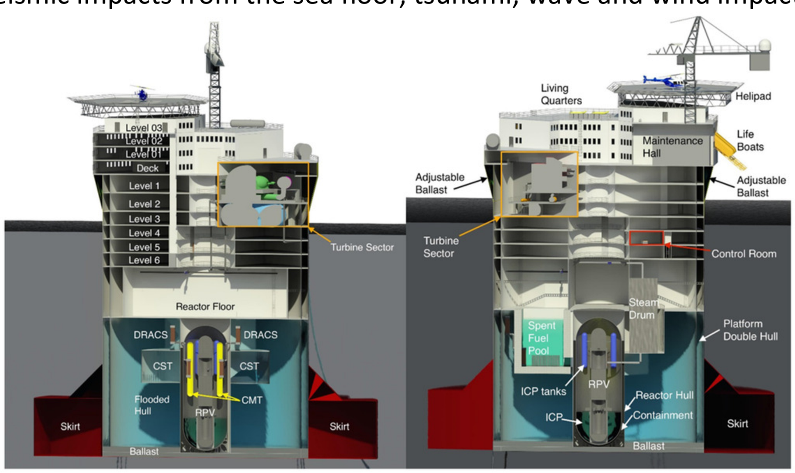

Fig. 4. 3-D cutaway view of OFNP

The reactor can be constructed without all structural concrete except radiation shielding. This fact definitely helps in reducing cost and construction time. Besides, the spar can create physical protection from plant crasher and collisions with ships as the reactor and containment being located at a level below the waterline. This OFNP can be located 10 to 20 km offshore with 100 m of water depth. The main deck can be 12.5 m above the water and the catenary mooring system. This allow the platform to move up and down in large amplitude waves, but restrain most lateral translation. The nuclear reactor also provides fresh water to the crew and plant via desalination process [19]. Figure 4 shows a cutaway view of this OFNP.

2.2.3 Gravity Based Structure (GBS)-type Ocean Nuclear Power Plant (ONPP)

The Gravity Based Structure (GBS) type ONPP is developed by Korea Advanced Institute of Science and Technology (KAIST) in South Korea. This concept actually makes use of an existing nuclear reactor, named the System-integrated Modular Advanced ReacTor (SMART) and the Advanced Power Reactor 1400 (APR1400) which developed by the Korea Hydro and Nuclear Power (KHNP) Co., Ltd. in Seoul, South Korea mounted on GBS. While modification of the general arrangement, safety features, and principal design parameters are minimal, and safety features against tsunami and earthquakes are being enhanced. This design makes use of the so-called modularization method to properly separate the NPP facilities into multiple GBS modules.

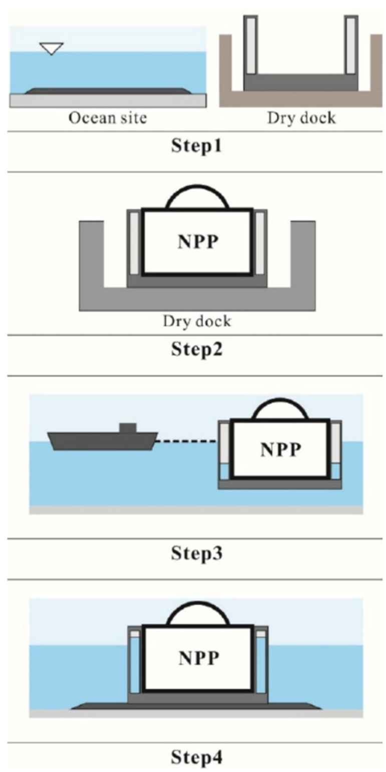

Fig. 5. Key concept of the GBS-type ONPP

The key concept of the GBS-type ONPP central on its use of a GBS as a container and a support structure in addition to the use of a modular design as employed in ship fabrication at an on-site factory facility. When the fabrication and assembly of the GBS and Nuclear Power Plant (NPP) components are completed, the GBS modules are launched and towed by tugboats to the ONPP mooring site. There, the modules are placed on the seabed using a ballasting system. Finally, the GBS modules are rigidly connected using steel bars, post-tensioning steel cables, and cement paste. At this point, the GBS modules act as a single rigid structure, thus mitigating risks related to pipelines and cables [19]. The details are shown in Figure 5.

2.2.4 Flexblue, the submerged type ONPP

In 2011, a submerged type ONPP, named Flexblue was proposed by DCNS (a defence group) from France. It is cylindrical, fully-modular, and transportable ONPP and was designed to reside on the sea bottom 60–100 m deep, up to 15 km offshore. Undersea cables would bring the electricity to customers, much like from offshore wind turbines. Preliminary studies showed that it is possible for Flexblue to produce anywhere from 50 to 250 MW of nuclear energy and researchers emphasize that the reactor is thought to be resistant to natural disasters such as earthquakes, tsunami, and flooding. When first announced, it was said that DCNS intended to start building a prototype Flexblue unit in 2013 in its shipyard at Cherbourg, for launch and deployment in 2016.

This submerged reactor uses the small pressurized water reactor technology, which is similar to the French submarine reactors. In the module of Flexblue, turbine and alternator sections are separated and partitioned. Flexblue is manufactured in factories, assembled in a shipyard using naval modular construction techniques, transported by the ship, and located at the operation site. Depending on the seismic hazard, the module is either anchored horizontally on the seabed, or suspended a few meters from the bottom of the ocean with positive buoyancy. The modules can be manufactured in different places and in parallel, allowing a shorter overall construction time [19]. An overview is shown in Figure 6.

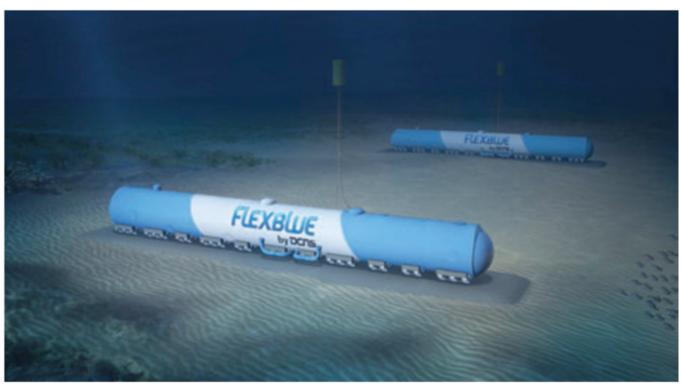

Fig. 6. Flexblue deployed, DCNS

2.2.5 The USS enterprise

The USS Enterprise is one of the most well-known mobile nuclear reactor. However, it is now undergoing deactivation. It is the world's first nuclear-powered aircraft carrier and the USS Enterprise is now 51-years old. It houses eight pressurized water reactors fuelled by highly enriched Uranium-235 fuel pellets. Due to the radioactivity, there wouldn't be much left to turn into a museum after decommission, so it is currently scheduled to take a final trip to Washington state for scrapping in

2015, though parts of it may be saved for a memorial. Figure 7 shows an outer view of the USS Enterprise.

Fig. 7. Outer view of the USS Enterprise

2.2.6 TES-3, the Soviet Mobile Nuclear Power Plant

The TES-3, the Soviets' Transportable Electric Station was designed in the USSR in the mid-1950s and is quite literally a mammoth, mobile nuclear power plant. At 310 tons with over 37 pounds of uranium on board, this nine-wheeled Soviet goliath was designed to haul nuclear power everywhere, that and the possibility of a Chernobyl-like disaster. The TES-3 never made it past the prototype phase, but not for lack of awesomeness or bounty of danger, but because it wasn't quite profitable. The project was scrapped in 1961. Figure 8 shows the photo of TES-3.

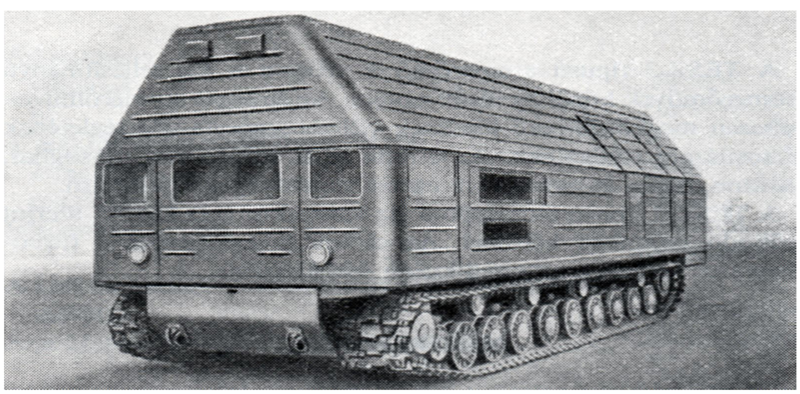

Fig. 8. The Soviet Mobile Nuclear Power Plant

2.2.7 SNAP-10A

The SNAP (Systems Nuclear Auxiliary Power Program) 10A which shown in Figure 9 was the first and only U.S. nuclear reactor actually launched into orbit, and made its way up there on April 3, 1965. The plan was for the SNAP to power huge satellites from orbit for at least one year, but just 43 days in, it failed due to a shoddy voltage regulator. For now, the remnants of the SNAP and its 37-rod payload are still up there, circling the Earth and will continue to do so for around 4,000 years. It should be interesting when it finally makes its way down.

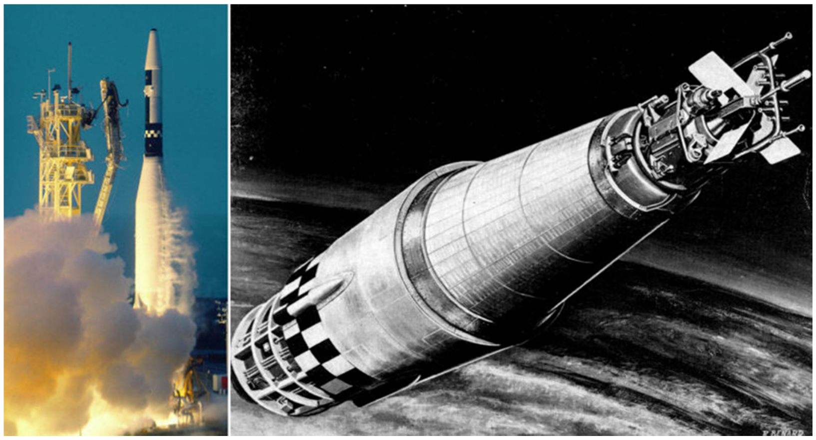

Fig. 9. The SNAP-10A

2.2.8 Kosmos 954

Like the SNAP, the Kosmos 954 was also a nuclear satellite, except Soviet in origin. It launched in 1977, fission reactor and 100 pounds of uranium on board, with the goal of long-term on-orbit observation. Like the SNAP, the Kosmos failed shortly after launch, but unlike the SNAP, it immediately careened back into Earth's atmosphere, spreading all kinds of nasty stuff over northern Canada. A good amount disintegrated on re-entry, and after a 10 month cleaned up operation, Canadian and American teams were able to remove about .1 percent of the atomic satellite's payload from the contaminated area (Nagy and Limer, 2012). Figure 10 shows the Kosmos 954.

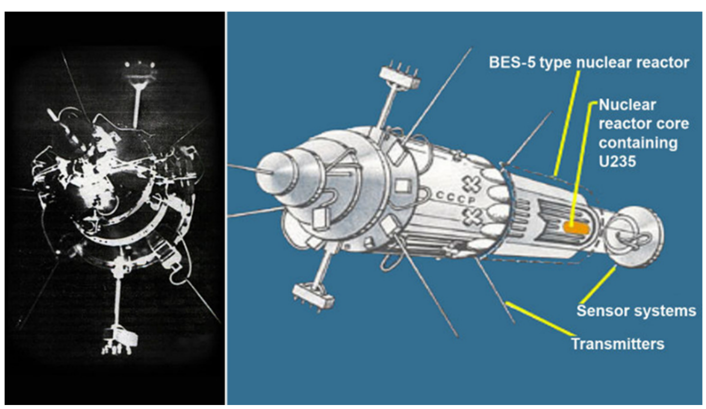

Fig. 10. Kosmos 954

2.2.9 Lenin

Lenin in Figure 11 was the world's first nuclear icebreaker and moreover, the first-ever nuclear powered surface ship. It was launched in 1957 with three pressurized water reactors but by 1970, all three had been replaced due to various incidents. Now it was decommissioned, in Murmansk where it serves as a hulking, once-nuclear museum.

Fig. 11. The Lenin

3. Evaluation and Selection of Nuclear Power Plant Types

Nuclear reactors serve three general purposes. Civilian reactors are used to generate energy for electricity and sometimes also steam for district heating; military reactors create materials that can be used in nuclear weapons; and research reactors are used to develop weapons or energy production technology, for training purposes, for nuclear physics experimentation, and for producing radio-isotopes for medicine and research.

Table 1
Types of Nuclear Reactor in the world

	PWR	BWR	PHWR	FBR	GCR
Fuel	UO_2	UO_2	UO_2	PuO_2 - UO_2	UC_2
Enrichment	Slightly enriched (3-5%)	Slightly enriched (3-5%)	Natural uranium	Various mixture	Slightly enriched (3-5%)
Moderator	Light water	Light water	Heavy water	Not required	Graphite
Coolant	Light water	Light water	Heavy water	Molten/liquid sodium	Carbon dioxide/ helium
Purpose	electricity	electricity	Electricity, plutonium production	Electricity, plutonium production	Electricity, plutonium production
Reactor Loop	2	1	2	3	1

A nuclear reactor produces and controls the release of energy from splitting the atoms of certain elements. In a nuclear power reactor, the energy released is used as heat to make steam to generate electricity. The principles for using nuclear power to produce electricity are the same for most types of reactor. The energy released from continuous fission of the atoms of the fuel is harnessed as heat in either a gas or water, and is used to produce steam. The steam is used to drive the turbines which produce electricity. The chemical composition of the fuel, the type of coolant, and other details important to reactor operation depend on reactor design. Most designs have some flexibility as to the type of fuel that can be used. Some reactors are dual-purpose in that they are used for civilian power and military materials production. Table 1 gives information about some nuclear reactors in the world.

To build a floating nuclear power reactor, some modification for the reactor has to be made. This report shows only the modification for Pressurized Water Reactor (PWR). Table 2 shows some modification of the PWR to fit the floating nuclear power reactor by reducing the size and the cost of the reactor.

Table 2
Modification on PWR to fit the floating nuclear power reactor

Current generation safety related systems	Floating nuclear power safety systems
High pressure injection system. Low pressure injection system.	No active safety injection system required. Core cooling is maintained using passive systems.
Emergency sump and associated net positive suction head (NPSH) requirements for safety related pumps.	No safety related pumps for accident mitigation; therefore, no need for sumps and protection of their suction supply.
Emergency diesel generators.	Passive design does not require emergency alternating current (AC) power to maintain core cooling. Core heat removed by heat transfer through vessel.
Active containment heat systems.	None required because of passive heat rejection out of containment.
Containment spray system.	Spray systems are not required to reduce steam pressure or to remove radioiodine from containment.
Emergency core cooling system (ECCS) initiation, instrumentation and control (I&C) systems. Complex systems require significant amount of online testing that contributes to plant unreliability and challenges of safety systems with inadvertent initiations.	Simpler and/or passive safety systems require less testing and are not as prone to inadvertent initiation.
Emergency feed water system, condensate storage tanks, and associated emergency cooling water supplies.	Ability to remove core heat without an emergency feed water system is a significant safety enhancement.

By having the reduction of the active cooling system and replaced by the passive cooling system, the reactor can be reduced and cut the cost.

4. Conclusion

There is growing interest in mobile nuclear reactors (MNRs) and their applications. MNRs are newer generation reactors designed to generate electric power up to 300 MW, whose components and systems can be shop fabricated and then transported as modules to the sites for installation as demand surfaces. Most of the MNR designs implement innovative or even inherent safety features and are deployable either as a single or multi-module plant. MNRs are under expansion for all principal reactor lines: water cooled reactors, high temperature gas cooled reactors, liquid-metal, sodium and gas-cooled reactors with fast neutron spectrum, and molten salt reactors. The significant driving forces of MNRs growth are satisfying the need for flexible power generation for a wider range of users and applications, replacing ageing fossil-fired units, enhancing safety performance, and offering better economic affordability.

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