

Floating Nuclear Power Plants and Associated Technologies in the Northern Areas



Reference:

Dowdall M, Standring W.J.F. Floating Nuclear Power Plants and Associated Technologies in the Northern Areas

StrålevernRapport 2008:15 Østerås: Norwegian Radiation Protection Authority, 2008.

Key words:

Floating nuclear power plants, northern areas

Abstract:

This report briefly presents the history and development of floating nuclear power plants (FNPP), introducing and discussing potential future implications associated with FNPP's in the northern areas.

Referanse:

Dowdall M, Standring W.J.F. Floating Nuclear Power Plants and Associated Technologies in the Northern Areas

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Emneord:

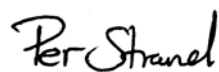
Flytende kjernekraftverk, nordområdene

Resymé:

Denne rapporten gir en kortfattet oversikt over historien og utviklingen av flytende kjernekraftverk med en presentasjon og diskusjon av potensielle fremtidige implikasjoner av flytende kjernekraftverk i nordlige områder.

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Approved:



Per Strand, Director, Department for Emergency Preparedness and Environmental Radioactivity

61 pages.

Published 2008-12-31.

Printed number 80 (08-12).

Printed by LoboMedia AS, Oslo.

Coverphoto: OKBM / IAEA

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www.nrpa.no

ISSN 0804-4910

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Østerås, 2008

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1 Background

In recent years Russia has striven to position itself internationally as a leading supplier of nuclear fuel, technology and services. This effort has been reflected in developments and restructuring in its political and economic structures to facilitate the expansion of the Russian nuclear industry. At the same time, severe power and heating shortages and general socio-economic under-development in the Russian northern regions and other isolated areas have precipitated a need for new power supplies in these regions. This need for power is also felt as the northern regions open themselves to exploitation of the vast resources present there. In combination with an earlier lack of new-build for conventional nuclear power reactors and the concomitant threat of decline in the nuclear industry, resurgent attention has been focussed on the development and implementation of new nuclear power initiatives of which low-capacity nuclear power plants (LCNPP's), for both the provision of domestic and industrial power and heat in isolated areas and for marketing internationally (for an overview see (1)), are a major part.

Although such plants may be used in land based power facilities (and have been at the Bilibino facility in the east of Russia), significant attention has been directed by Russia towards the deployment of LCNPP's in floating nuclear power plants (FNPP's), which are essentially large barges with one or more LCNPP's and related facilities installed. The FNPP concept is then envisaged, within the context of its broader commercial potential, to form the basis for a solution to power and heat requirements in the Russian north and east and for a number of specific power provision concepts that may be marketed internationally. This attention has arisen in an international climate that has, since the early 1990's, begun to focus on LCNPP's and FNPP's as a solution

to a range of problems precipitated by a changing international energy and security situation exacerbated by the pressures of environmental and climate changes and shifts in economic factors pertaining to fossil fuels.

A wide range of countries are either developing or have developed LCNPP designs and a number of these concepts are already under construction or at advanced stages of product development. A larger number of countries have expressed interest in foreign supplied LCNPP's as solutions to problems ranging from domestic power and heat provision, industrial heat provision, hydrogen production, desalination and as power sources for resource extraction. For power plants providing less than 300 MW, a number of initiatives are worth noting as indicative of the range of activity in this area. All these designs are characterised by small size, advanced design, short construction times and suitability for a range of applications. All are designed for potential supply to third party customers internationally. Examples include:

- The Long Operating Cycle Simplified BWR (LSBWR) design of Toshiba Corp., Japan (100-300 MW(e)).
- The CNEA/INVAP CAREM-25 design from Argentina (27 MW(e))
- The SMART (System-Integrated Modular Advanced Reactor) of the Republic of South Korea (90 MW(e)).
- Mitsubishi's (Japan) Integrated Modular water Reactor (IMR) (300 MW(e)).
- Russia's KLT-40S heat and power floating reactor unit (75 MW(e)).

The advantages of LCNPP's were recognised very early in the evolution of nuclear power technology as they were seen as an elegant solution to problems requiring autonomous power sources not requiring fuel delivery in remote locations. Research programs for the development of LCNPP's were initiated in the

early 1950's by the United States for the Dept. of Defence and a number of plants were developed based upon a wide range of reactor designs (gas/water/liquid metal cooled) in a wide variety of different configurations (stationary/modular/mobile etc). The actualised power plants were designed with power capacities in the range of 0.3-3.0 MW(e) and examples of such LCNPP's were built and installed in areas such as Alaska, Antarctica and Greenland (2), primarily for heat and power provision to military facilities and troop garrisons. All such plants were removed and decommissioned at various times during the 1960's.

Around the same period, the then USSR began development of its own LCNPP program and this resulted in a design suite of approximately 20 variants in the range 1.0-1.5 MW(e) with a similar breadth to the US program in relation to reactor type and configuration (3). A brief overview of some of the more recent Russian designs is provided in Table 1. The decision to actually develop prototype LCNPP's was taken in 1956 and at various times after that experimental LCNPP's were built and operated at various locations, mostly as research test-beds. Work throughout this period resulted in reactor designs such as "Elena" and the Pamir-630D mobile systems went on to be designed and developed during the 1980's. The 1970's saw development in the USSR of LCNPP's for use in remote military bases and in military and civilian vessels. By the 1980's focus had shifted towards power provision for remote regions and settlements and potential site identification at this time resulted in 33 prospective locations for LCNPP's within the territory of the USSR.

The next phase of development began in the 1990's and in 1991 a special scientific/industrial entity, now known and publicly traded as JSC Malaya Energetika, was established by a range of Russian concerns (including Rosenergoatom, a Russian nuclear

power stations operator) of which the stated objectives, as of today, are twofold:

- To expand Russian and overseas markets for small capacity nuclear power plants based on a floating power unit utilising KLT-40S reactors and complex desalinating units on the basis of floating nuclear power plants.
- To draw up a package of programmes for the financial analysis and assessment of the social and economic efficiency of small size nuclear projects on the basis of floating power units utilising KLT-40S reactors.

JSC Malaya Energetika has thus shifted from the original focus towards the general development of LCNPP's to one orientated towards the development and international marketing of FNPP's and desalination facilities based on LCNPP designs. This is not to say however that other concerns in Russia have ceased to design, develop or market LCNPP's for both FNPP's and other purposes and LCNPP's outside of the FNPP concept remain an area of appreciable commercial and practical interest in Russia. From the period of the establishment of JSC Malaya Energetika a general time-line can be established as to development of both interest in LCNPP's in general and FNPP's in particular, both as technological advancements and as practicable, commercially viable systems, both aspects being of particular relevance to the Arctic regions as will be discussed.

In the first half of the 1990's, JSC Malaya Energetika conceived of and held a public design competition for the best design of LCNPP technology, not being limited at that time to iterations for FNPP use. The winning proposal was submitted by Atomenergo, an entity formed by a range of bodies including Afrikantov Experimental Machine Building Design Bureau (OKBM) (Nizhny Novgorod),

Designation	Reactor type	Output	Run period	Reference
ATU-2	Water-graphite channel system	26 MW(e) 58 MW(t)	2 years	(4)
KLT-40S	Water cooled/moderated, floating	2 x 38 MW(e) 2 x 85 MW(t)	3-4	See section 2.3.1 for discussion.
VBER-300	Water cooled/moderated	150–600 MW(e) variants	2	(5)
RUTA	Water cooled/moderated, natural circulation	4 x 55 MW(t)	7	(6)
ABV-6M	Floating, integrated water cooled/moderated, natural circulation	8.6 MW(e) 12 MW(t)	10	(7)
MARS	Molten salt reactor	5 MW(e) 8.5 MW(t)	30 to 60	(8)
Elena	Water cooled/moderated	0.07 MW(e) 2.6 MW(t)	25	(9)

Table 1. Overview of recent Russian LCNPP designs.

the Nizhniy Novgorod Machine Building Plant, the Iceberg Central Design Bureau in St. Petersburg, the Baltic Shipyard of St. Petersburg, and Atomflot located in Murmansk and the design was based on the use of two modified KLT-40 nuclear power plants (see section 2.3) on a floating, barge-like, non-propelled platform. This particular design was intended initially as a replacement power plant for a coal burning facility based in Pevek, Chutotka. By the middle of 1996, plans were announced in the international media for the building of up to 15 FNPP's (based, according to these reports, on the Atomenergo KLT-40 design) for the Russian Far East. The plans were for the first unit, for intended installation near Pevek, to be operational by the end of 2001. The end of 1996 saw announcements in the media that the technical design stage of the process was complete (10).

Throughout 1997 information as to a related development manifested itself in reports of the conversion of the nuclear power vessel "Urals"

to an FNPP (11) with a variety of media sources reporting that construction/conversion was to begin in 1998. Various conflicting reports were made in a variety of sources through 1998 on the actuality of the use of nuclear powered submarines for provision of power to remote bases (12) and it appears that the results of activities in this direction did not indicate that such measures could provide a realistic long-term solution for a number of reasons.

More concrete plans were outlined in 2000 detailing the construction of the first Russian FNPP to be conducted, reportedly, at the Baltic Shipyard in St. Petersburg. The plan was said, at that time, to be awaiting administrative approval. The following year however Yevgeniy Adamov (then Atomic Energy Minister of Russia) announced that FNPP construction was to take place at the Sevmash facility in Severodvinsk with the first FNPP to provide power for the Sevmash facilities and the adjacent city of Severodvinsk. At that time

it was decided that Pevek was not to be the first location for an FNPP due to technical and financial considerations. More definite details became known in 2002 as Aleksandr Rumyantsev (Atomic Energy Minister of Russia between 2001 and 2005) approved designs for FNPP's based on the modified KLT-40S reactor systems and indications were then made that the project had received positive environmental impact statements. Official approval for the project was made by the parliament of Arkhangelsk Oblast and in October 2002, Gosatomnadzor (the Russian Federation's nuclear regulator) issued the necessary licence for siting of the plant at Sevmash/Severodvinsk. The first reliable indications of potential international customers for the FNPP concept were forthcoming in 2002 with delegations to China in relation to FNPP's, financing, and technology transfer and documents were signed in May 2003 indicating the possibility of co-financing of the Severodvinsk FNPP (13) and possible Chinese construction of the barge upon which the FNPP was to be placed.

Indonesia indicated in 2003 its potential interest in Russian supplied FNPP's as power solutions (14) although it later became apparent that the power requirements of Indonesia were such that a land based larger facility was more suitable. Vladimir Asmolv (Deputy Atomic Energy Minister) announced in November of 2003 that feasibility studies for the Severodvinsk FNPP had passed inspection and that construction would commence between 2006 and 2010 at the Sevmash facility, declarations of intent being signed for construction of FNPP's for Vilyuchinsk (Kamchatka Oblast) and Pevek. In June of 2006, the head of RF Federal Agency, S.V. Kirienko, and the Head of Administration of Arkhangelsk Region, N.I. Kisilev, signed approval for the building of an FNPP at Sevmash and contracts were signed with Sevmash and other relevant bodies for the building of the plant. On the 15th of April 2007, construction began on the FNPP *Academician Lomonosov* at the Sevmash yards

with construction to be complete by 2010 or earlier. The *Academician Lomonosov* will be the first FNPP to be built since the *Sturgis* (see section 1.1) and will, it appears, serve as a "proof of concept"/prototype, establishing the technical viability of the Russian FNPP concept. In 2008 it was announced that further construction would be conducted at St. Petersburg.

Over the same period (1990 through to the present) and concurrent to progress regarding FNPP's, the development and international marketing of the concept of FNPP's as power sources for desalination plants and other purposes was also underway and consideration of FNPP's as power sources for oil and gas extraction was also elaborated upon. These aspects are discussed at a later stage in this report.

1.1 Floating Nuclear Power Plants (FNPP's) - history

The concept of floating nuclear power is not totally new with respect to design, implementation or technology and the *Academician Lomonosov* is not, as often appears in the media, the first FNPP. As early as 1963 work began in the United States to convert the World War II liberty ship, *Charles H. Cugl*, to a floating nuclear power plant utilising a high power pressurised water reactor (type: MH-1A) of > 10 MW. The propulsion unit of the original ship was removed and the entire midsection replaced with a 350 t steel containment vessel and concrete collision barriers. The containment vessel contained not only the reactor unit itself but the primary and secondary coolant circuits and electrical systems for the reactor. Conversion was completed by 1967 and the vessel (now technically a barge), re-named *Sturgis*, was operative in Virginia in 1967 before being moved to the Panama Canal region to be used for power generation for both military and civilian use. The vessel remained there until late 1976 when the authorities controlling the canal decided more land based power capacity was required and *Sturgis* was moved back to

the United States for decommissioning, having generated power over a period of 9 years.

The barge reached its destination at Fort Belvoir in Virginia in March of 1977 and the decision was taken shortly after to deactivate the reactor due to damage sustained in rough weather on the Atlantic crossing (which had necessitated repairs en route) and for military finance reasons. At the time of deactivation, the nuclear fuel was removed, some decontamination took place and sections of the barge were sealed off. The decision was then taken to place the barge in “storage” to allow decay of contaminant radionuclides and it was envisaged at that time that decommissioning would be completed in 2027. 89 m³ of solid radioactive waste and 363 m³ of liquid radioactive wastes were removed from the ship and processed. Deactivation of the barge was completed in 1978 and since then the barge has been in “safe storage”. Activities towards finally decommissioning the vessel commenced in 1998 and are ongoing. Further information may be found in U.S. Army Corps of Engineers (15,16).

Throughout the 1970’s floating nuclear power was considered a viable technological and economical concept by the US and various initiatives were taken with a view towards implementing such systems for the provision of domestic power. These steps included the formation of a company (Offshore Power Systems) to develop the concept and the construction of yards for FNPP construction. Two plants were designed (designated Atlantic -1 and -2) and were based upon installation of two 1200 MW reactors on large, permanently moored, barges. Development proceeded on building the construction facility and Blount Island off Florida became the site for the construction yards for the plants. Plans at that stage were to build 4 plants a year. Commencement of construction coincided with the passing of legislation in the US regarding environmental impact assessments and the finished assessment concluded that the plants

represented no major impact on the environment. The oil crises of the 1970’s served to reduce the need for electricity by major oil refineries and petrochemical concerns and as these were projected to be the main customers for FNPP generated electricity, the plans were eventually abandoned.

In the early 1980’s the provision of offshore power in the far north was studied in Russia, progress advancing as far as feasibility studies for the use of proposed designs for, amongst other purposes, oil and gas drilling and power provision for remote areas. Among these early designs, a model based on water-cooled and moderated ABV-1.5 reactors was elaborated upon by Golovin et al. (17). The design, perhaps the first fully elaborated upon, was denoted *Sever* and was intended to have a thermal capacity of 3000 MW and electric power provision of 3000 kW from each of the two ABV-1.5 power units on board the proposed vessel. *Sever* was not intended to be self propelled but rather towed by tug vessels and had a proposed length of 84 m, breadth of 21 m and a draught for offshore operation of approximate 3 m making it somewhat smaller although still similar in shape and style to the current designs for FNPP’s. The plant was intended to be relatively self contained over its intended operational life (in excess of 10 years) and had provision for maintenance, repairs, refuelling operations and the volume reduction of high and low activity wastes which were to be stored on board prior to delivery to some central facility.

The shielding design of this early FNPP model was relatively complex in nature, experience from the *Sturgis* having apparently influenced the designers and representing a transition between the *Sturgis* and current designs. The shielding design consisted of two parts: the first integral to the steam-producing unit itself and to be transported with the vessel and the second to be removable shielding that could be removed from the vessel when the reactors were not in operation during transport of the

vessel from location to location. The reactor was designed to be as compact as possible and shielding of the reactor itself was to be achieved using lead (between 3 and 7 cm thick depending on location) and borated water. Supplementary shielding was to be effected using the non-active components of the steam-producing unit. The removable shielding was presumably concrete or steel or a combination of both and the amount of this shielding was intended to be sufficient to reduce the draught of the vessel from 3 m to less than 2 m upon removal to facilitate river navigation. Relative to the current design of FNPP's the *Sever* concept was low powered (approx. 6 MW(e) as opposed to approximately 70 MW(e)) and was more orientated towards the operation of oil and gas boring rigs.

FNPP's today appear, when viewed in relation to earlier development, to represent no real technological or engineering barriers, the idea being some 45 years old in both inception and actualisation and the fundamentals of the concept having already been tested and improved upon for approaching half a century in the Arctic environment by the Russian civilian fleet without major incident. Given the maturation of the techniques involved in the use of nuclear reactors aboard civilian vessels and advances in reactor design and fuel technologies, a concept such as FNPP's would probably be unlikely to be ignored in the current international economic and security climate, especially with respect to efforts to deal with the implications of climate change. This is firmly evidenced by the significant activities of the International Atomic Energy Agency (IAEA) in this area which has completed a number of Coordinated Research Projects (CRP's) on the matter of FNPP's, LCNPP's and their use in a variety of fields. Irrespective of the use of FNPP's solely as power/heat providers, it is the flexibility of the concept of FNPP's that has generated much of the interest in the concept.

1.2 Possible Uses of FNPP Technology.

It is important to note that FNPP's constitute but the basis for a number of implementations of potentially significant commercial interest and that development of the concept in Russia has occurred in tandem to the development and marketing of a number of "power solutions" of interest internationally but that may not actually be deployed in the Russian Arctic. That these products will most likely be developed and built in, and subsequently transported through, the Arctic and Northern marine environment is however of potential consequence and therefore of some interest.

The most significant of these developments from a commercial point of view (which is ultimately what will most likely decide the ultimate commercial future of FNPP's outside of Russian territory) is in respect to the development, supply and servicing of nuclear powered facilities dedicated to the desalination of salt water for the supply of potable water.

1.2.1 FNPP: Desalination

The problems many nations face in establishing and securing freshwater supplies need little elaboration: United Nations data indicates that the current freshwater shortfall worldwide is running at some 230×10^9 m³/yr and will rise to 2×10^{12} m³/yr by 2025 (18). Large-scale desalination has long been used for freshwater provision in a number of countries and demand for desalinated water is predicted to double every decade. The use of nuclear energy as a power source for energy demanding desalination plants is a very attractive option for many nations. Japan, Kazakhstan and Pakistan all operate nuclear powered land based desalination plants and a large number of nations operate fossil fuel powered desalination plants of various sizes. FNPP development in Russia has proceeded in step with the concept of using such technologies for nuclear powered desalination plants and it is possible that desalination will

be a major factor in the commercial future of FNPP's worldwide in the coming years. There are no significant technological or engineering barriers to the use of FNPP or other nuclear sources for powering desalination facilities but the economics of using such facilities is obviously a major consideration. In this respect the recent general conclusions of the IAEA Co-ordinated Research Project "*Economic Research on and Assessment of Selected Nuclear Desalination Projects and Case Studies*" (19) are worth noting:

- Nuclear desalination systems are technically feasible and economically attractive options for a range of sites and using a variety of nuclear reactor concepts,
- The cost of nuclear desalination may be 30-60% lower than the most economical fossil fuel based system and nuclear desalination systems will be competitive as long as gas prices remain above 150 \$/toe.

The IAEA lists the following main advantages to the use of FNPP's in desalination facilities:

- FNPP's may be manufactured and tested at ship-building facilities, using industrial technologies allowing for improvement in quality and reduction in cost,
- FNPP design adheres to non-proliferation requirements because repairs, refuelling of the reactor and radioactive waste/ spent nuclear fuel handling are performed at specialized facilities of the FNPP supplier at the same time as FNPP overhaul.
- FNPP's can be decommissioned and replaced with new FNPP's whilst preserving the established shore-based infrastructural facilities.

- FNPP's can ultimately be disposed of at the specialized facilities of the supplier.

With respect to Russia's views on nuclear desalination as a marketable technology, the conclusions from the Russia input to the CRP (20) were:

- "*Floating nuclear power desalination complex with the KLT-40S reactors, coupled with MED (multiple effect distillation), has been considered as the most probable option for nuclear desalination in Russia.*"
- The cost of desalinated water produced was evaluated, and based on KLT-40S and RITM-200 reactors, desalination costs are lower than fossil fuelled driven systems if oil prices remain above 90-120 \$/t.

Internationally, socio-economic, climate and security concerns have resulted in increased attention on nuclear desalination. Results of international and national assessments demonstrate the cost-effectiveness and technological feasibility of such systems and this is evidenced by the fact that countries such as Canada, China, Pakistan, Japan, Argentina, Morocco and Israel have either built such plants or are in the process of designing or building new facilities and a suite of the nations are interested in using commercial solutions. Although Russia itself has a small (but not insignificant) requirement for desalination facilities (21), the potential international market and Russia's strategic positioning as a leading developer and potential supplier of FNPP technology internationally would appear to indicate that the Arctic could become the location for industry and activities related to the provision, servicing, refuelling and decommissioning of FNPP based desalination plants as well as FNPP's built for use in the Russian north and elsewhere. As of 2002 Argentina, Canada, China, Egypt, France, India, Indonesia,

Pakistan, the Republic of Korea, Morocco and Tunisia had ongoing programmes at various stages for the deployment of nuclear power for desalination purposes (22; 23) and it is from among these countries that Russia has identified potential customers for FNPP desalination plants. Media coverage indicates that Russia is actively marketing the concept around the world on a number of different levels. Whilst the use of nuclear powered desalination facilities by these countries is of little direct consequence for the Arctic region or Norway, the manufacture, servicing, refuelling and transport of such facilities in and through the Arctic, in addition to the land based industrial infrastructure required, is obviously a matter of some interest.

1.2.2 FNPP: other uses

A range of potential uses for which FNPP's may be viable technologically and economically have arisen in the past decade amplifying the commercial prospects for the technology. The original Russian designs for FNPP's as demonstrated by the *Sever* concept indicate that from the start of activities related to FNPP development, application of FNPP's for powering oil and gas extraction has always been an incentive. It has recently been reported in the media of the commencement of activities to convert the *Sevmorput* to a nuclear powered drilling vessel by 2010 (24) and the concept of powering oil and gas extraction at the Shtokman field in the Barents Sea has led to statements by Norwegian concerns, environmental organisations and Russia on the matter. The opening up of Arctic areas for oil and gas exploration and the difficulty of powering such extraction has left FNPP's well positioned as a possible solution. Related to this positioning are the mineral resources of the Russian far north and east where lack of power has hindered extraction, a problem that may be solved by using FNPP's to power such activities. New developing technologies such as hydrogen production or extraction of metals from brine concentrates produced as a waste product from desalination have also been

highlighted as potential areas for FNPP deployment.

1.3 Potential Locations for FNPP's

A range of locations has been mentioned over the years, both officially and unofficially, in the media and other sources as potential or planned locations for FNPP's. In total, between 50 and 80 separate regions have been reported to have expressed interest in siting FNPP's. During an international conference entitled "*Small Power Plants: Results and Prospects*" held in Moscow on 10th - 11th October 2001, Minatom stated that some 33 towns in the Russian far north and far east will be powered by small nuclear power plants and of these, 11 power plants will be floating and will be constructed for Severodvinsk and Onega (Arkhangelsk Oblast), Vilyuchinsk (Kamchatka Oblast), Pevek (Chukotka Autonomous Okrug), Sovetskaya Gavan and Nikolayevsk-na-Amure (Khabarovsk Krai), Nakhodka, Olga and Rudnaya Pristan (Primorskiy Krai), Dudinka (Taymyr Autonomous Okrug), and the site of the Trukhanskaya hydro-electric plant (Evenkiyskiy Autonomous Okrug) (see Figure 1). Aside from the potential positioning of FNPP's at the above, the possible use of FNPP's in oil and gas extraction implies that wherever such activities take place there is the possibility of FNPP's being sited to provide power. As mentioned, the Shtokman field near the Kola Peninsula has featured in discussions of the employment of FNPP for the provisioning of power in oil and gas extraction. In principle, any sizeable town outside of the main power Russian grids and adjacent to water of a sufficient depth, is amenable to power provision by FNPP. Any resource deposit in a remote location or where power provision is difficult is also a potential siting for an FNPP. The current designs of the FNPP barges are such that they are able to travel in quite shallow water and this opens up the interior of Russia along the major large river systems. Locations outside of Russia's far



Figure 1. Potential locations of FNPP's in the Arctic region. Grey shaded areas indicate locations of oil or gas exploration areas where FNPP's could be employed as power sources. Arrows indicate potential routes from an assumed manufacturing/servicing centre in the Arkhangelsk region to international customers or Russian locations outside of the Arctic.

north, such as sites along the Sea of Japan which have featured strongly as possible sites, will necessitate transport of FNPP's both to, and, perhaps more significantly from a security/environmental point of view, back from such sites, travelling along routes through the Arctic and potentially along the Norwegian coastline. Russia has and is actively marketing

FNPP/desalination solutions to a number of countries including Argentina, China, Indonesia, Chile and others. Assuming that some of these countries enter into agreements for the provision of such technology from Russia, the potential for increased transport to and from these countries increases, some of this transport potentially travelling in waters near Norway.

1.4 Commercial realisation

It is only possible to consider the commercialisation of FNPP's within the larger picture relating to nuclear power and Russia's intentions. Russia's nuclear energy system has undergone and is undergoing a major restructuring and reorganisation that is preceding the planned large-scale expansion of nuclear energy within Russia. These plans have been initiated from the highest levels of the Russian political system where the potential of nuclear power both as an energy source for Russia and as a major export opportunity have been recognised. The first clear indications of this reorganisation has been the consolidation, as a result of Presidential decree signed on the 27th of April 2007, of a number of nuclear fuel cycle companies into one large organisation known as AtomEnergProm which is in effect a government owned holding company. The decree of April 2007 concludes a series of legislative initiatives, which began in early 2006. Towards the end of that year the government of Russia adopted *The Federal Targeted Program on the Development of Russia's Atomic Energy Complex* which had been devised by Rosatom and which sets out Russia's industrial plans forward to 2016. The aims of this program are domestic nuclear expansion and the radical expansion of Russia's share of the international nuclear market to something approaching as much as 20% of international nuclear trade.

In the second planned stage of this reform, nuclear design and the nuclear construction industries will be consolidated and possibly merged into AtomEnergProm. In October 2007 a legislative proposal was made to Parliament to create the Rosatom Corporation, as distinct from Rosatom agency, to manage all nuclear assets on behalf of the state. The results of these two steps will be the formation of an industrial nuclear complex that will be of sufficient size to compete effectively on the international nuclear market for large contracts

with established and similarly scaled entities such as AREVA, ENEL, Siemens and Toshiba.

Russia's domestic expansion of its nuclear power program fulfils two purposes: replacement of its old nuclear facilities and provision of new ones to support its expanding industrial capacity and, secondly, the reduction of domestic pressure on its fossil fuel resources, freeing them up for increased export which earns Russia valuable access to foreign currency. Projected expansion of Russian nuclear capacity is by two plants per year forward to 2030 leading to an installed capacity of 40 GW(e) by 2030 with an expected export of 20 GW(e) capacity over the same time frame. Earlier plans much reported in the media as to Russia's intention to import SNF and radioactive waste have been clearly and resolutely denied by the head of Rosatom recently (25). Internationally Russia has consolidated its position with respect to delivery of nuclear technology and related services with the *Global Nuclear Infrastructure Initiative* (GNII) announced by Russia in mid-2006. This initiative is complementary to other international moves such as the IAEA's MNA (*Multilateral Approaches to the Nuclear Fuel Cycle*) proposal of 2005 and the GNEP (*Global Nuclear Energy Partnership*) of the United States. Within the framework of the GNII, Russia would work with respect to four distinct objectives: the first would be to host an International Uranium Enrichment Centre, the second a reprocessing and SNF storage facility and the second two would relate to training of personnel for emergent nuclear countries and the research and development. It can thus be seen that FNPP's play a significant part of both Russia's commercial intentions regarding nuclear power and its international activities and that development of the concept has taken place within an environment that is more and more focussed on the delivery of nuclear solutions as a commercial enterprise. There is little doubt that Russia is viewing FNPP's as a viable commercial concept and an important part of its domestic and international strategy

regarding nuclear power. The exact specificities of how FNPP and associated technology is to be brought to commercial realisation is a little unclear and the current construction of the *Academician Lomonosov* appears to be more a proof of concept than an example of a production system. Polushkin et al. (26) provides some indications of the commercialisation concepts' background and it is unlikely that the major points have changed significantly in the intervening years. The manufacturers will market the technology on a "Build-Own-Operate" scheme whereby the ownership of the facility is retained but the products (heat and electricity) are sold to a another party. It is stated by the authors, who are affiliated to JSC Malaya Energetika, JSC Atomenergo, JSC Iceberg and OKBM, that Rosenergoatom (unclear whether this will be the existing agency or the proposed corporation) will be the owner and financier and operate the facility thereby removing the burden of heavy capital investment from the end users and consumers. The owners will staff the facility with trained operatives and thereby hope to use their experience gained in relation to civilian nuclear vessels in the running of FNPP's. The intended benefits to the consumer include safe and secure power supplies with reduction or elimination of the reliance on fossil fuels and concomitant benefits in relation to reduction in mining activities, pollution reduction, stimulation of industry etc. The owner will enter into a long-term agreement with the consumer and settle upon a tariff for the purchase of heat and power provided by the FNPP. A feasibility study will then be entered into and upon conclusion the construction of shore-based infrastructure will commence to be completed within 2 or 3 years. The plant itself will then be constructed and put into place. This is expected to take 5 years for building and 1 year for transport and installation. The plant (in this instance it is being assumed that the KLT-40S design is being used as an example) is designed to hold enough fuel, and to have sufficient space and handling capacity for SNF and radioactive waste, to function for 12-15 years. At the end of this time the plant, with its SNF and waste,

will be removed and towed to a designated facility in Russia, for overhaul, waste removal etc. This overhaul is anticipated to take 1 year. The life cycle of the FNPP is two overhauls and 3 operating cycles or 40 years overall. It should be noted that as of 2007, no "Build-Own-Operate" has ever been implemented with regard to civilian nuclear power facilities although there has been a precedent regarding leasing of a nuclear submarine by India from Russia. The entire concept relating to the commercialisation of FNPP (and desalination systems) is not novel but it is a breakthrough in that it is the first time the concept would be applied on a large scale. The system could be envisaged as solving many problems related to the processes involved in trying to locate sites for land based nuclear facilities which have often presented a significant problem for countries evaluating nuclear power as an energy option and some aspects of non-proliferation. Russia is not the only country looking at this option to solve problems in relation to marketing nuclear services; Australia and a number of other states (including the US) have evaluated such systems for expanding their own nuclear industries. In the case of Australia, nuclear fuel would be leased (Australia would retain ownership) by a second country and once exhausted, Australia would be responsible for removing it, storing/reprocessing it and supplying fresh fuel. Russia's focus therefore on this idea for bringing FNPP's to commercial reality is in-step with developments internationally regarding future business models for the nuclear industry.

Irrespective of how FNPP's are dealt with commercially once built and delivered, the production of small reactors in relatively large numbers over quite short time periods to demanding specifications requires a different industrial model with respect to production and insight into the direction of thinking on this point can be found in (27) where discussion and analysis of production models are discussed. The authors conclude:

“when transition is made to the construction of nuclear power plants with unified equipment and largely factory made structures delivered to the site, substantial reserves of cost reduction can be realised at all stages of the life cycle of the plants and therefore the capital costs and production cost of energy can be lowered”.

The current thinking would therefore appear to envisage a serial production of standardised reactors and components in relatively large volume as opposed to contracting, design and building of individual reactors as would be the case for large one-off facilities. An interesting (and recent) insight into the nature of commercialisation and production of FNPP's is a record of an interview conducted with the deputy director of Rosatom, Sergey Krysov in November of 2007 (28). This interview indicates that the serial production techniques that have been used for icebreaker and submarine reactors will be adapted for production of FNPP's and that serial production of the systems is viewed as an important way to reduce overall costs and thereby increase and maintain competitiveness in a market that, the interview indicates, Russia does not expect to have a monopoly in. It should be noted that the principle that the costs of nuclear power plants can be reduced, thereby making them more commercially viable, was one of the major factors in Westinghouse's pursuit of the concept of FNPP's in the 1970's. Russia however has modified the notion slightly by viewing serial production of standardised small reactors as opposed to serial production of larger (< 1 GW) reactors.

1.5 The FNPP Industry: Supporting infrastructure

1.5.1 Existing facilities

The construction, maintenance, refuelling, decommissioning and storage/handling of SNF and waste from FNPP's and associated nuclear

powered facilities require significant shore based specialised infrastructure. Russia already has extensive facilities at a number of locations (see Figure 2) that have been involved in such operations with respect to its nuclear military and civilian fleets. It is possible that, at least in the early years of commercialisation, the infrastructure used to support FNPP's will be based around Russia's extant infrastructure for the support of its civilian nuclear fleet. This is primarily based around the facilities of the Murmansk Shipping Company at Atomflot, some two kilometres from Murmansk. It has recently been announced that Rosatom (29) has taken over the icebreaker fleet and the facilities at Atomflot, a move which it may be argued could facilitate the use of these facilities in the support of an FNPP industry under the auspices of Rosatom. Operations at Atomflot in relation to the civilian nuclear icebreaker fleet include:

- Maintenance and repair work on vessels, systems and equipment; refuelling nuclear reactors;
- Preparing spent fuel for transportation to storage/reprocessing sites;
- Receiving, processing and temporary storing of SRW and LRW.

Atomflot has significant infrastructural assets for the type of operations involved in maintaining nuclear vessels and is connected to the national railway system for transport of nuclear wastes and SNF to appropriate facilities. Circumstances have, at times, been less than optimal with respect to handling of waste and storage of SNF at the Atomflot facility and these aspects have been of concern over the years. Atomflot has handled LRW for both the civilian nuclear fleet and for at least some of the Northern fleet since the mid 1990's. Annual capacity throughout the 1990's was 1200 m³ of LRW and this was due to be increased to some 5000 m³ as a result of international collaboration. Atomflot storage capacity for LRW is some 100-200 m³ in two



Figure 2. Existing locations related to the civilian and military nuclear fleets of potential significance to an emergent FNPP industry in Northwest Russia.

tanks designed for temporary storage only. Atomflot has storage facilities for approx. 400 m³ of SRW and has facilities for the handling of flammable radioactive wastes. The site also has facilities for the storage of high level SRW such as reactor parts etc. Atomflot has special facilities such as scrubbers; filter systems etc. to ensure protection of the environment from

contamination as a result of its operations. A number of service vessels are based at Atomflot and it is these vessels that have proved to be of most concern with respect to how radioactive waste and SNF has been handled and stored. The service vessels *Imandra*, *Lotta* and *Lepse* have been used for the storage of large amounts of waste and SNF

under non-optimal conditions and remain a significant problem with respect to risks of radioactive contamination of the environment.

The Sevmash shipyards are located at Severodvinsk near Murmansk and it is at this yard that construction of the “*Academician Lomonosov*” commenced and at which it can be assumed at least some if not all future Russian FNPP’s will be built. Sevmash is one of the biggest yards in Russia and has been engaged in building nuclear submarines for the Russian navy and has also been the site of dismantlement of nuclear submarines. Sevmash has approximately 2500 m² of storage space for radioactive wastes consisting of both open and closed areas. Most waste generated at Sevmash is removed to facilities such as Sayda Bay on the Kola Peninsula for storage. Only small amounts of waste are generated at Sevmash. The shipyards have been undergoing upgrading with respect to SNF and fresh fuel handling and waste storage since the mid 1990’s.

A second shipyard near Severodvinsk is the Svezdochka yard that is the smaller of the two yards at Severodvinsk and was initially involved in the repair of nuclear submarines. Zvezdochka possesses a floating dock, three fully equipped docks, repair and machine buildings and auxiliary workshops. As a result of its work with submarine dismantlement, Zvezdochka has three specialized areas for sectioning of submarine hulls. Problems with rail communications between Zvezdochka and the Mayak facility prevented direct shipment of SNF and for twenty years up to the early 1990’s, SNF was transported to Murmansk for further shipping. This practice stopped in 1993 and since then the facility has received significant amounts of SNF and radioactive wastes for storage. This was conducted using support barges. The yards also have an incinerator for SRW.

The Nerpa shipyard located at Olenya Bay, is mostly engaged in the repair, maintenance, and dismantlement of generation nuclear-powered submarines. The yard has a dry and a floating dock outfitted for defueling and readying submarines for fresh fuel, and equipment for transferring SNF to Malina-class service ships or other facilities. Nerpa also has storage facilities for SRW and as of 1996 contained 200 m³ of solid radioactive waste and 170 m³ of LRW.

The majority of nuclear icebreakers have been constructed at the Baltic Shipyards in St. Petersburg but the initial construction phase of the “*Academician Lomonosov*” at Sevmash indicates that it cannot be assumed that support of FNPP’s as a commercial product will be confined to the facilities or infrastructure associated primarily with the nuclear icebreaker fleet.

1.5.2 Potential risks with FNPP shore based infrastructure

Although there is little information as to the potential nature of any FNPP industrial development with respect to facilities and infrastructure, it is pertinent to examine the types of problems experienced in the past in the related civilian fleets. Such an examination serves to highlight potential future problems for an FNPP industry based on past experience. In general the operations and equipment of the civilian nuclear fleet have accorded with all relevant international and national regulatory instruments. The main problems associated with the operation of the fleet have been related to the handling and storage of SNF and associated wastes. The situation concerning, for example, the *Lepse* storage vessel is a cause for concern although it is possible that improvements in the general Russian nuclear industry would mean that such a situation is unlikely to arise again. Operations at Atomflot have included a number of aspects that may pose a threat of environmental contamination. These include gas releases from reactors on

vessels and from stored SNF during the first months of its storage. The concentrations of such gasses outside of reactors on board nuclear icebreakers and during refuelling operations have never exceeded Russian radiological safety norms (30). Icebreaker reactor cores over four years of operation generate waste volumes of the order of 130 m³ of LRW and 32 m³ of SRW most of which is subsequently treated and handled at the Atomflot base. Studies have shown that despite these operations and the handling of significant amounts of SNF and radioactive waste at the Atomflot site, significant contamination of Kola Bay has not occurred although traces of contaminant isotopes can be observed at levels that give no cause for concern (30).

The operations of the civilian nuclear fleet have, over the years, not generated the sort of environmental risks or problems associated with the military fleet where shore based facilities have been the cause of concern for many years due to large amounts of badly stored SNF and waste in hazardous condition. Of the civilian fleet and the military fleet, it would appear logical to assume that any FNPP industry would most resemble the civilian fleet's operations and would be run in a similar manner. Given the advances in the general Russian nuclear industry with respect to safety and environmental awareness since the Chernobyl accident of 1986 and the necessity for an FNPP industry to compete and gain acceptance on the open market it would appear unlikely that such an industry could allow a situation to develop whereby problems of the past, in particular with respect to sites associated with the military fleet, would be replicated.

1.6 Availability of Information

The progress of Russian plans towards the development and commercialisation of FNPP technology has mostly been disseminated through the media which complicates the situation with respect to reliability. Some statements that appear in the media are

confirmable or supporting information is available through more reliable sources. Some open sources of use in following the progress of the development of FNPP technology as a commercial enterprise are:

- The website and information services of the IAEA,
- Nuclear industry information services,
- The Foreign Broadcast Information Service (FBIS) of the CIA Directorate of Science and Technology,
- The information services of Rosatom, Sevmash and JSC Malaya Energetika.

2 Technical details relating to FNPP's

There has been extensive conjecture since the late 1990's as to designs and technical implementations of FNPP's, much of this speculation having arisen due to the number of the large number of designs having been put forward for the Malaya Energetika competition and the fact that FNPP/LCNPP design has been ongoing over a long number of years with numbers of variants for each individual design. It is only in the past 6 or 8 years that the picture has clarified itself somewhat due to the survival of a limited number of designs and the presentation of these designs in various reports and projects allowing reasonable conclusions to be drawn.

2.1 FNPP Design

Russia is well positioned (if not best positioned globally) with respect to the design and operation of FNPP's and LCNPP's. It is the only country in the world that has operated a civilian nuclear icebreaker fleet and is approaching the 50th anniversary of the beginning of its civilian nuclear fleet operations in 1959. Russia also possesses an extensive, long-established and experienced research and design establishment well positioned to form the basis of an industry involved in the innovative deployment of new reactor designs. For an overview see Kostin et al. (31). Russia's total operational record with respect to nuclear powered civilian ships has long exceeded 150 reactor years and reactor equipment on board the civilian fleet has been in operation in excess of 120'000 reactor hours. These records have been established in the extreme conditions of the Arctic (where FNPP's are projected to be employed) and Russia has accumulated significant experience in the development and operation of civilian nuclear powered vessels in ice floes, under conditions of constant manoeuvring, ice impacts and vibration which are exactly the conditions under which FNPP deployment is

envisaged. That this environment is harsh is undeniable but it should be remembered that American intentions were to deploy even larger reactors in a hurricane prone area off Florida's coast; conditions which necessitated the building of breakwaters consisting of 18000 80 t concrete structures for each FNPP. During the past 4 decades there have been no recorded incidents involving loss of chain reaction control or large-scale releases of radioactivity from Russian civilian vessels during their routine operation.

2.2 Barge design

A reasonable amount of information from a variety of sources is available as to the physical nature of the currently under construction at Sevmash FNPP *Academician Lomonsov*. The following information is drawn primarily from IAEA-TECDOC-1391 (32) and Polushkin et al (26). The vessel is to be a non-propelled, smooth-decked barge like construction, some 140 m in length and 30 m wide. Board height to the uppermost deck will be 10 m and the maximum draught is to be 5.6 m. Total displacement with full removable cargo complement prior to operation is expected to be 21500 t. Permanent personnel complement is to be 58 with 12 temporary. The period between factory services for the barge is to be 10-12 years with a total operational life of 40 years. The barge is to have a sharpened bow and straight stern with three decks and the entire vessel is to be divided into 10 compartments by a series of 9 watertight bulkheads. Projections are that any two adjacent compartments can be flooded for all loading configurations without the vessel sinking in accordance with Russian regulations as to ship design. The barge is also outfitted with systems for fire fighting and radiation control facilities. A diesel generator is provided to ensure power supplies for water provision to the reactor in the event of an accident.

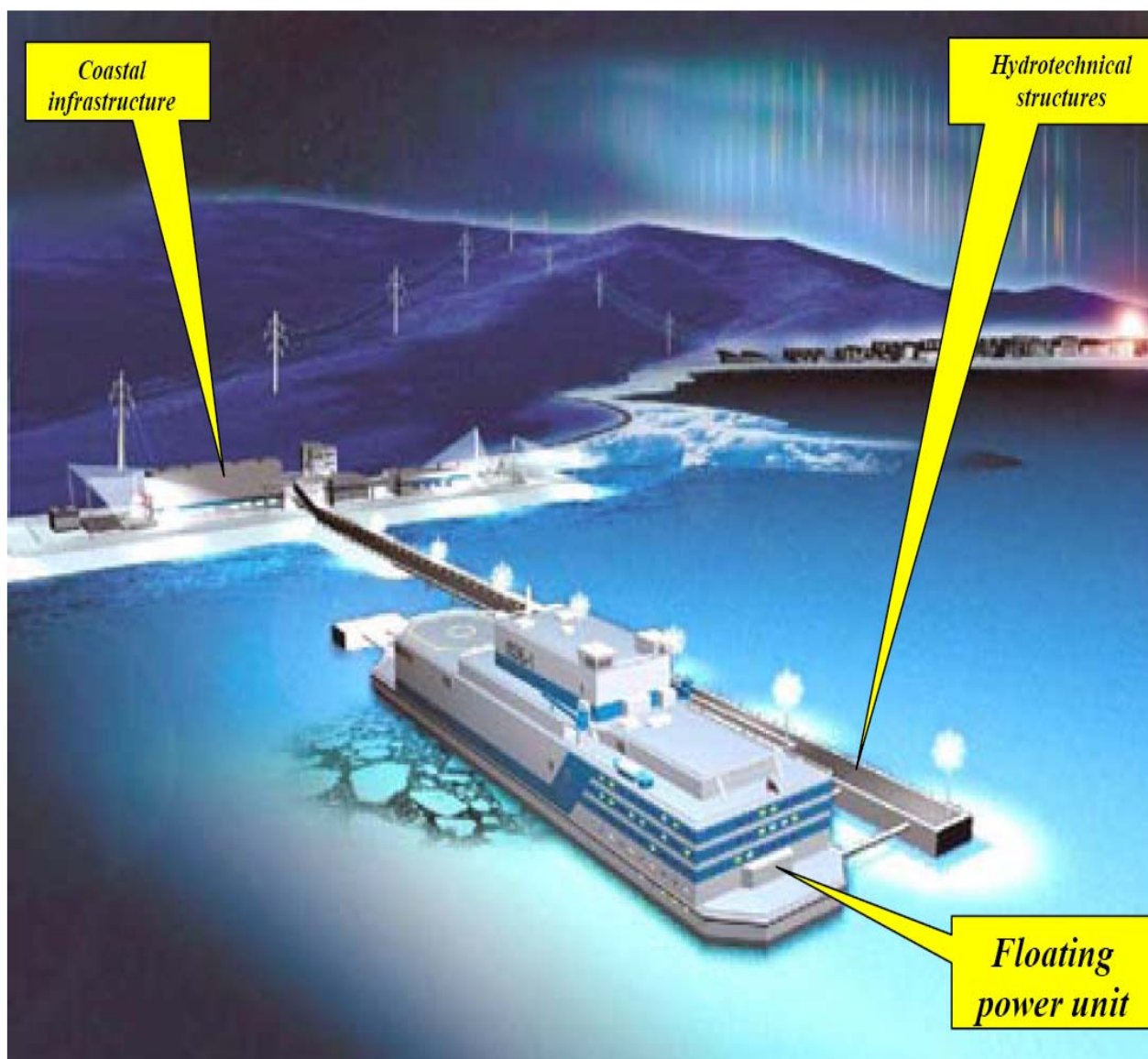


Figure 3. Depiction of the currently under construction *Academician Lomonosov*. Source: OKBM / IAEA (32).

An artist's depiction of the *Academician Lomonosov* is depicted in Figure 3 and a schematic is provided in Figure 4. Associated shore based facilities for power and heat transfer and ancillary services occupy ca. 1–2 ha. The FNPP will have onboard facilities for the storage of spent nuclear fuel (SNF) and solid and liquid radioactive wastes (SRW and LRW). Refuelling equipment is also present. Although available details are somewhat lacking, it is expected that the barge will be at least partially surrounded by a pontoon or

barrier on the seaward sides, designed presumably to prevent problems with ice floes or collisions. The expected total sea area for the barge and associated structures such as the pontoon is some 6 ha. For other FNPP designs, such as those incorporating the smaller more compact ABV-6M reactor design (see section 2.3.3 and Figure 4), the barge will be proportionally smaller (2500 t displacement) or potentially larger for some of the proposed designs utilising bigger reactors. ⁷Vasyukov et al., (2004) provide indicative barge dimensions of (length x breadth x displacement)



Figure 4. Left: Schematic of barge design for “Academician Lomonosov” based on the KLT-40S design and currently under construction. (source : OKBM/IAEA-TECDOC-1391(32).Right: Schematic of vessel using the ABV-6M reactor design. Figures not to scale. Source: IAEA (33).

80 m x 14 m 2300 t for a single unit ABV-6M plant and 67 m x 12 m x 1600 t for a single unit ABV-3 plant. The draught of both these barges is described as being less than 3 m which means such facilities could navigate waters that larger KLT-40S plants could not, thereby opening up significant areas of Russia's interior for their use.

In an apparent deviation from the single barge concept for the *Academician Lomonosov* and the ABV-6M design, it appears that barge design for an FMPP utilising the larger VBER-300 (see section 2.3.4) reactor will be significantly different. The basic design is for a non-propelled barge related to the "pillar-class" of vessels as described in Russia's Sea Navigation Register classification. The barge will have three pontoons, the reactor plants (two are called for in some designs) being located behind each other as opposed to side by side on the central pontoon. Each reactor plant consists of a reactor plant, a plant control room, an electrical plant and areas for refuelling and repair. Each plant is housed in a steel containment vessel and nuclear fuel storage is positioned between the two reactor units. Electrical equipment such as transformers and facilities required for transfer of power to shore based facilities are located on one of the peripheral pontoons and back up equipment such as generators etc are located on the other peripheral pontoon. Each pontoon is 170 m in length and 19 m wide with a total pontoon height of 12 m. Total displacement of the entire FNPP is 49000 t. The plant is designed to be overhauled every 20 years with a total service life of over 60 years. Kostin et al (5) describes a catamaran barge design denoted as PAES-150 for use with a single VBER-300 reactor displacing some 25000 t. Some details of safety aspects of barge design are provided for the ABV proposed plants in IAEA-TECDOC-1536 (33). These include the incorporation of shock absorbers for protection against wind loads and seismic loads as well as shock absorbing systems within mooring structures. A collision protection system of steel plating and a structural framework to

prevent the penetration of a crashing service helicopter into the reactor containment and structural systems of steel to mitigate the effects of a side collision with another vessel. To prevent a grounding event from impacting upon the reactor containment, the bottom of the containment is separated from the protective vessel shell by corrugated sections in the vessels bulkheads.

2.3 Reactor design

2.3.1 KLT reactor variants.

The winning reactor design for Russian FNPP's (JSC Malaya Energetika competition) was based upon use of a modified version of the established KLT-40 reactor type. The KLT-40 reactor plant (see Table 2 for some reactor details) is a well established and long-proven design that has been employed in Russian nuclear powered vessels for approximately 20 years and is the power plant for vessels such as the icebreaking freighter *Sevmorput* with the two icebreakers, *Taimyr* and *Vaigatch* using a higher power variant known as KLT-40M (both of which utilise one such reactor each).

The KLT-40 design and details of it are relatively well known as technical details of the reactor were provided to Norway during a visit of *Sevmorput* to the port of Tromsø. Full details of the KLT-40, its implementation in *Sevmorput* and other Russian marine reactors may be found in Reistad and Ølgaard (34). The KLT-40 core is some 1 m tall and 1.2 m in diameter and utilises 241 fuel elements in a triangular lattice with spacing of 72 mm. Each fuel element has 53 fuel pins of outer diameter 5.8 mm. The fuel itself was reported to be uranium zirconium alloy of 90% enriched ^{235}U in a zirconium cladding with a total load of 167 kg of uranium. Shielding of the reactor in *Sevmorput* was a metal-water shield with concrete on the top parts. The containment system for the KLT-40 was the same as that of the Russian OK-900 plants and was constructed such that any radioactivity released was held within the containment and pressure

Parameter	KLT-40	KLT-40S	KLT-20	VBER-150 Partial refuelling	VBER-150 Full core refuelling	VBER-300	ABV
Reactor characteristics							
Designers	OKBM	OKBM	OKBM	OKBM	OKBM	OKBM	OKBM
Power – Thermal MW(t)	135	2 x 38	70	440	350	850	18-60
Power – Electric MW(e)		2 x 85	20	150	110	295	11
Fuel type	U-Zr mix	UO ₂ silumin matrix	Pelletised UO ₂ /inert matrix	Pelletised UO ₂	Pelletised UO ₂	Pelletised UO ₂	UO ₂ silumin matrix
Fuel enrichment	90%	< 20%	< 20%	< 5%	< 5%	< 5%	16.5%
Coolant/Moderator	H ₂ O/H ₂ O	H ₂ O/H ₂ O	H ₂ O/H ₂ O	H ₂ O/H ₂ O	H ₂ O/H ₂ O	H ₂ O/H ₂ O	H ₂ O/H ₂ O
No of elements in core	12773	12342	-	26520	-	-	-
No. of fuel assemblies in core	241	121	121	85	85	85	121
Core height mm	1000	1300	1800	1500	2200	2200	1300
Core diameter mm	1210	1219	1219	2420	2420	2420	1219
Element cladding	Zr alloy	-	Zr alloy (E110 or E635)	Zr alloy (E110 or E635)	Zr alloy (E110 or E635)	Zr alloy (E110 or E635)	Zr alloy (E110 or E635)
Average burn up	-	-	1.8 g ²³⁵ U/MWday	50.0 (MWday)/kgU	31.3 (MWday)/kgU	50 (MWday)/kgU	94.5 (MWday)/kgU
Refuelling interval		3 -4.5 years	10 years	4-6 years	10 years	-	10-12 years
Uranium inventory t	0.16	-	1.68	-	-	10	1.4
Reactor height mm	-	-	9000	14750 mm	-	12500	7500
Reactor diameter mm	-	-	2176	-	-	3700	2600
Reactor weight, t	-	-	150	590	-	-	85.7
Reactor material	Anti- corrosive steel	Anti- corrosive steel	Anti- corrosive steel	Anti- corrosive steel	Anti- corrosive steel	Anti- corrosive steel	Anti corrosive steel
No. of circuits/loops	-	-	2	2/2	-	-	2
Primary circuit flow rate t/h	-	-	1650	7265	710	-	397
Coolant temp at core inlet °C	273	-	289	292	291	-	247
Coolant temp at core outlet °C	316	317	317	330	322	320	330
Primary circuit pressure MPa	13	12.5	12.7	15.7	15.7	15.7	15.7
Max fuel cladding temp. °C	-	-	330	352	352	-	434
Max permissible fuel temp. °C	-	-	550	2500	2500	-	900

Table 2. Summarised information for some Russian reactor designs for implementation in FNPP designs.

regulating valves stayed open such that in the event of sinking destruction of the containment would be prevented. The modified version of the KLT-40 reactor, the KLT-40S (Figure 5), often denoted as KLT-40C through translation, has been described in varying levels of detail in a number of publications (21; 32) and some details are provided in Table 2. The reactor appears to have a slightly different

construction to the KLT-40 with reduced steel cladding on the walls and increased water-metal shielding resulting in a slightly wider reactor vessel. For the FNPP implementation, the KLT-40S is to be installed in pairs. The overall dimensions of the KLT-40S in its containment housing are 7m by 7m and 11 m in height.

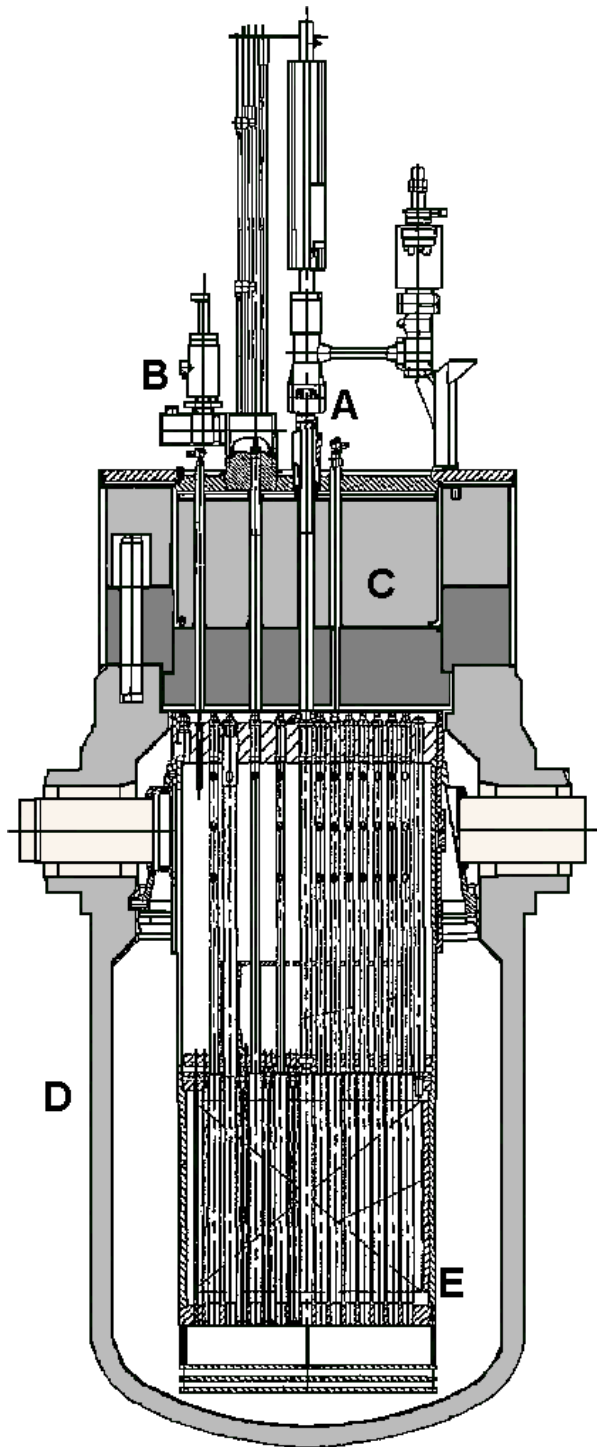


Figure 5. Schematic of the KLT-40S reactor. A – compensating group (CG) drive system, B – emergency protection (EP) drive system, C – cover, D – reactor vessel, E – removable core. Source: Beliaev and Polunichov (35).

The KLT-40S reactor core is designed to a $3.3 \cdot 10^6$ MW·hr specification indicating a life cycle of some 22000 hours. The duration of operation without refuelling is expected to be of the order of 3 to 4 years depending on the exact enrichment level of the fuel. The KLT-40S is a two circuit PWR (forced circulation in the primary circuit) reactor, the main reactor plant itself comprised of the reactor, the steam generating plant and pumps connected by the main pipe conduits and forming a steam generating “block” (see Figure 6 and 7). The reactor itself consists of a forged and welded, thermally stable steel reactor vessel with anti-corrosion facing, a removable block and core with neutron absorbing EP rods and compensating group (CG) drives. Steam generation is achieved by a once-through coil type heat exchanger with titanium alloy coils, the generation vessel itself being of alloy steel with anti-corrosive facings. The primary circuit pump is a centrifugal design with a predicted capacity of $870 \text{ m}^3/\text{hr}$ at pump head of 0.38 MPa and is constructed of stainless ferrite steel. The above section is based on information from IAEA-TECDOC-1326 (23) and IAEA-TECDOC-1391 (32) and further details may be found in these publications.

A further variant of the KLT-40 basic design is that known as KLT-20 as described thoroughly in IAEA-TECDOC-1536 (33) that is again specifically designed for the FNPP concept. This variant is a PWR reactor with an electrical power capacity of 20 MW(e). It is a two-loop modification of the KLT-40S design and appears to have been specifically designed to eliminate problems associated with the relatively short refuelling interval of the KLT-40S. Utilising the KLT-20 in an FNPP would therefore remove the need for storage of fresh fuel and SNF on board the vessel and refuelling and waste removal would occur during return to base servicing operations. The general layout of the reactor systems are similar to those described for the KLT-40S.

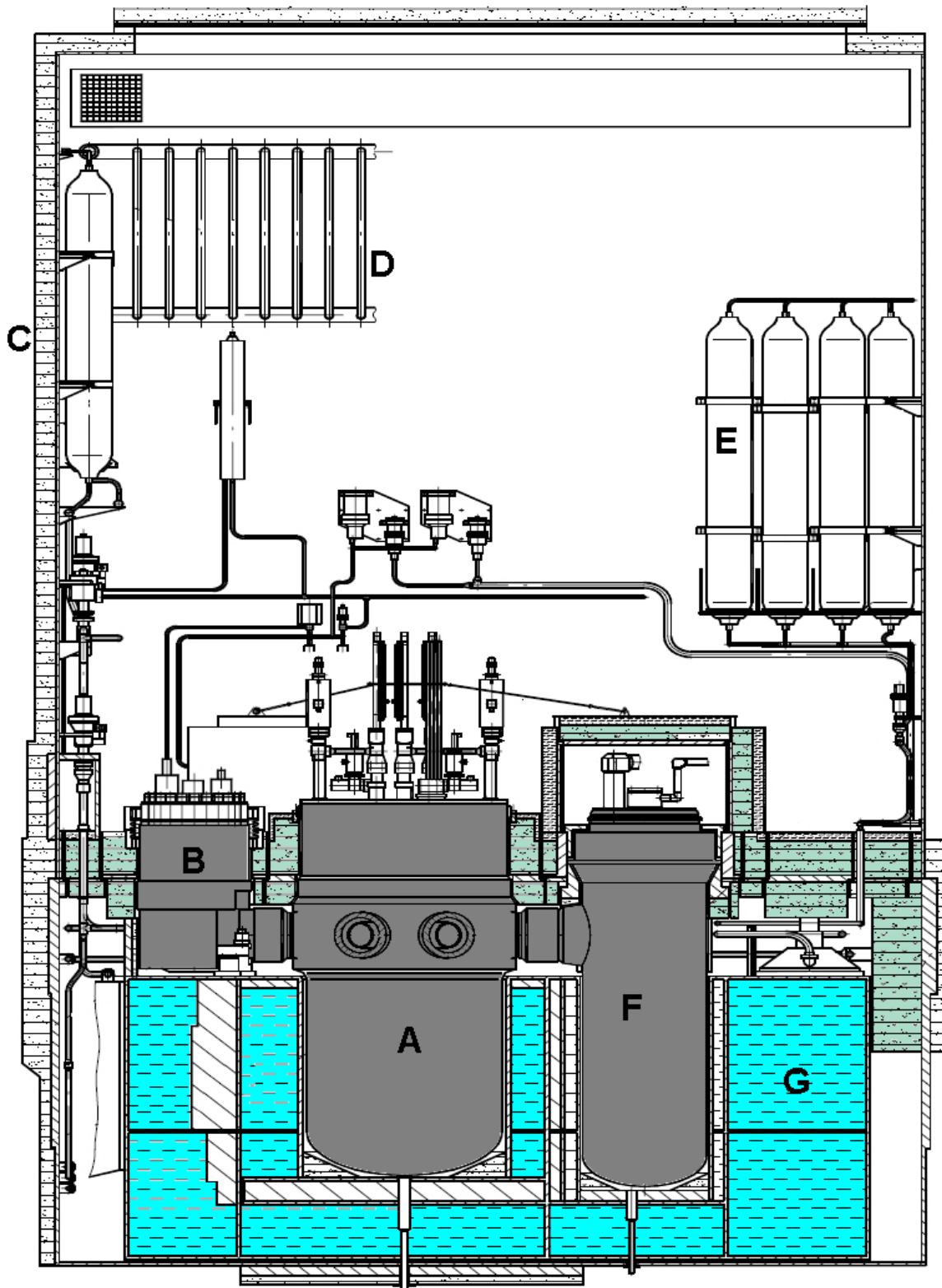


Figure 6. KLT-40S reactor compartment. A – reactor vessel, B – Main circulation pump, C – containment shell, D – emergency pressure condensation system, E – high pressure gas, F – steam generator, G – water-metal radiation shielding. Source: Beliaev and Polunichev (35).

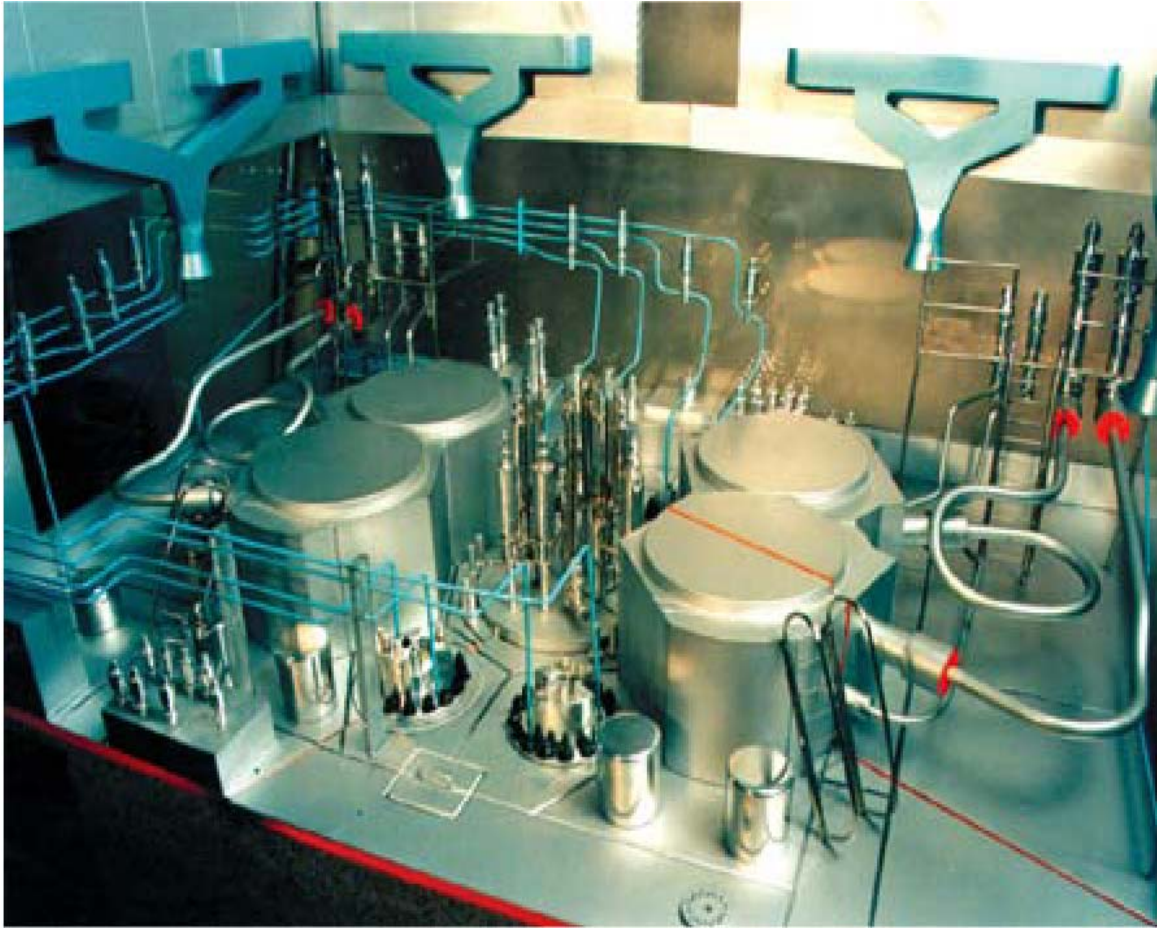


Figure 7. General view of the proposed KLT-40S reactor plant. Source: OKBM/IAEA,(32).

2.3.2 VBER reactor variants.

The VBER-300 (5) is a 295 MW(e) PWR unit intended to be installed in pairs for high capacity floating power generation on a barge displacing some 49000 t or in a single reactor variant displacing 25000 t. The total thermal capacity of the unit (single reactor) is 850 MW. A variant of the VBER-300, the VBER-150 has a power capacity of 110 MW(e) and is usually described as a two-loop modification of the VBER-300 (figures 8 and 9). The reactor (both variants) design features a high degree of compactness, the reactor and steam generators being connected by very short pipes to ensure a small volume for the system.

The fuel for the VBER-300 is reported to be pelletised uranium dioxide with a gadolinium burnable poison in the reactor. The refuelling interval for the VBER-150 is indicated to be of the order of 7-8 years and is described as having a long operational cycle removing the need for storage or fuel handling operation on site, all such activities (including waste handling) being conducted at specialised service centres. Two operational modes for the VBER-150 are generally described, the first being a partial refuelling of the reactor after approximately 320 days of operation and the second being the previously mentioned fuel refuelling after long cycle. The VBER 300 variant has a refuelling period of between 3 and 6 years.

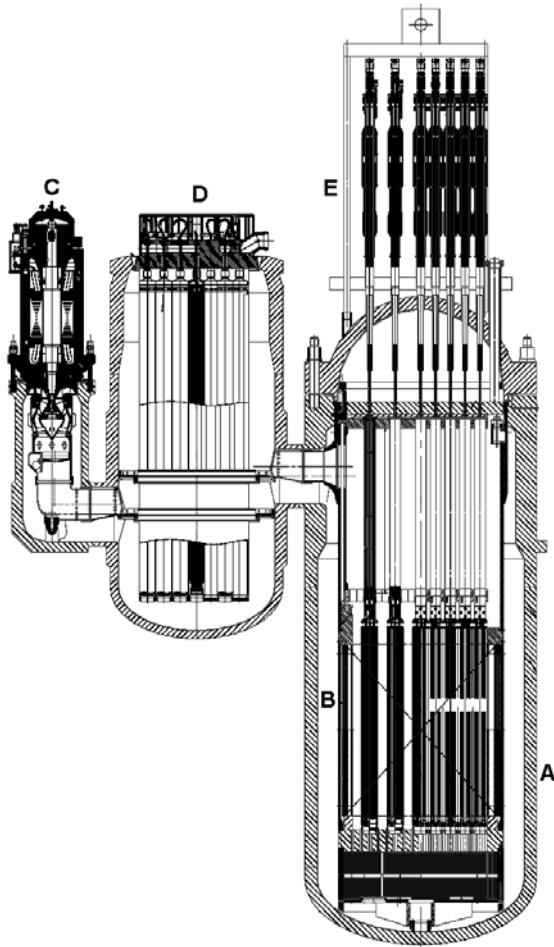


Figure 8. VBER-150 reactor. A – reactor vessel, B – reactor core, C – Coolant pump, D – steam generator, E – control and protection systems. Source:OKBM / IAEA,(33).

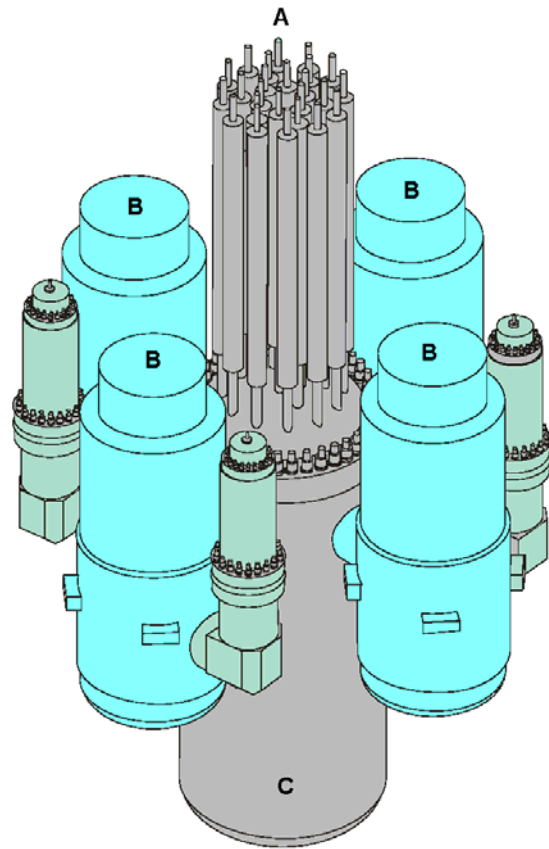


Figure 9 . VBER-300 reactor. A – control and protection systems, B – steam generators, C – reactor vessel. Source:OKBM / IAEA,(33).

2.3.3 ABV reactor variants.

The ABV reactor variant consists of a number of designs all featuring similar construction. In general they are water cooled modular reactors with an integrated steam generation unit. The ABV-6M is a small water cooled and moderated compact reactor design described by Kostin et al (36) and Baranaev et al (37) and is one of three ABV designs all potentially usable in FNPP's although concrete designs only exist for the ABV-6M. This range of reactors is as follows with thermal capacities as indicated: ABV-3 (18 MW(t)), ABV-6 (38MW(t)) and ABV-6M (47 MW(t)). The thermal capacity of the ABV-6M can be increased to 61 MW(t) by modification of the reactor core and associated steam

producing systems. The ABV-6M utilises a similar core to the KLT-40S and has 121 fuel assemblies. The expected core lifetime between refuelling is 8-10 years with an expected lifetime of 50 years. The reactor features integrated steam generation (see Figures 10) and the whole reactor weighs approximately 600 tonnes. The design features a range of passive and active safety systems and its small size is being viewed as an attractive option for river transport etc.

A range of other reactor types are described by a variety of design bureaus and other enterprises but the majority of these are either conceptual, only at the design stage or are not intended to be used on FNPP's.

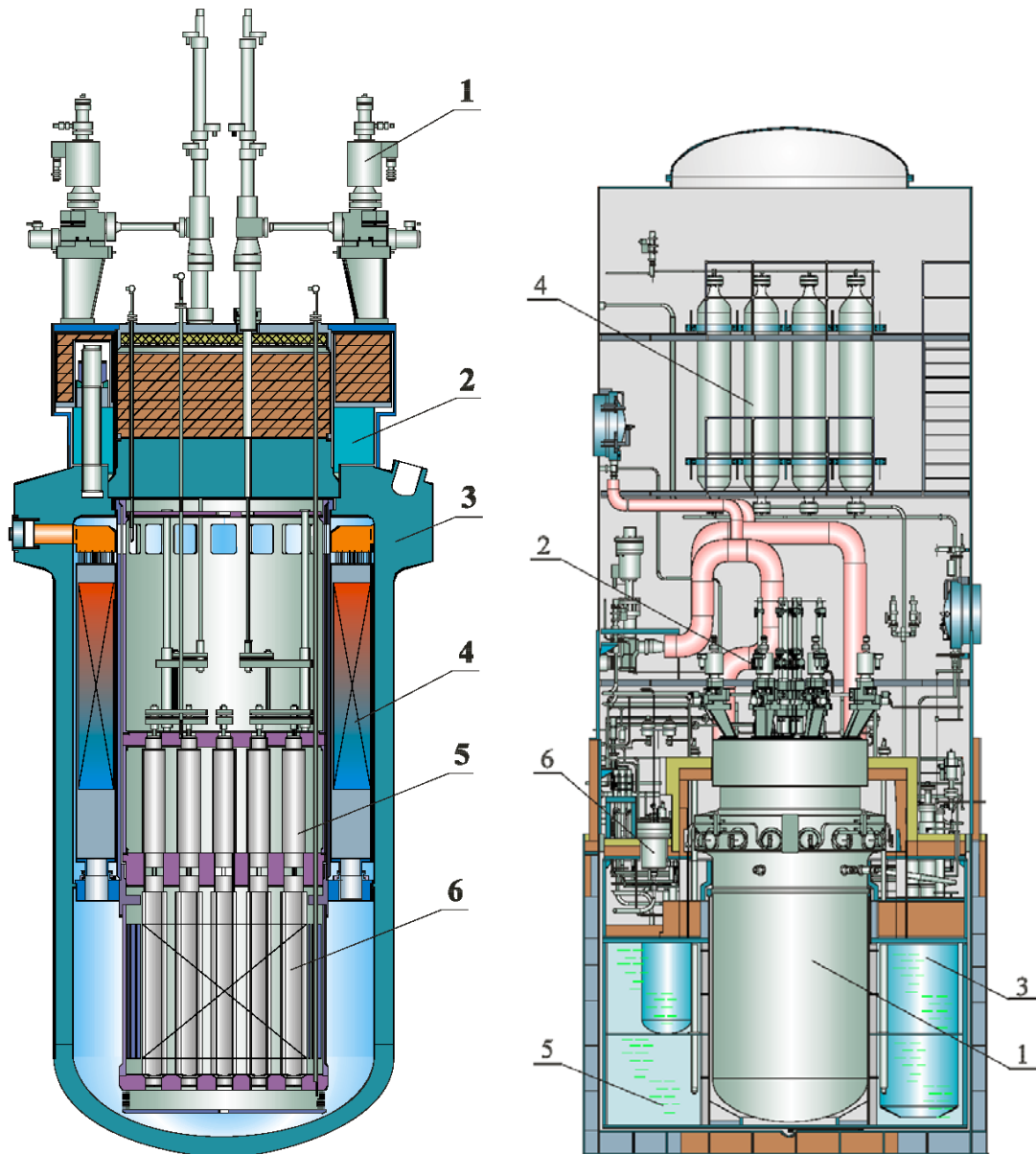


Figure 10 . Left – ABV-6M reactor : 1.Control rod drop mechanism, 2. Cover, 3. Reactor vessel, 4. Steam generator, 5. Protective tubes unit, 6. Reactor core.

Right – ABV-6M and ancilliary equipment : 1. Reactor, 2. Control rod drop mechanism, 3. Pressurizer, 4. Gas cylinders, 5. Metal –water shielding, 6. Purification and cooling system pump.
Source:OKBM / IAEA,(33).

There has been much discussion as to the fuel type to be used in the KLT-40S, primarily from a non-proliferation point of view, and thus the discussion has focussed on the enrichment level of the fuel. Glaser and von Hippel (38) pointed out the importance of

ceasing the use of highly enriched uranium as fuel in reactors such as the KLT-40 and pointed out that work appeared to have been commenced in Russia on fuel using lower levels of enrichment perhaps directed at useage on a “different purpose water reactor”. The exact level of enrichment for the KLT-40S has been a matter of some debate (see for example

Diakov et al (39); Nilsen and Bøhmer (40). Belyayev and Leontyev (41) indicate that probable fuel for the KLT-40S will be “ceramic metal fuel” with “<20% enriched uranium” in order to meet non-proliferation requirements. A discussion of potential zirconium matrix fuels is provided by Savchenko et al (42) stating that:

“These fuel elements are also usable in FNPP reactors under development...The uranium density in this fuel is 4-5 g/cm³ which tolerates the use of 20% ²³⁵U and meets the IAEA proliferation requirements”.

The description of the fuel elements in this report again reinforces the fact that enrichment of < 20% is required for non-proliferation purposes. The level of ²³⁵U enrichment is also given in (32) as not exceeding 20%. Perhaps the clearest indication as to the enrichment level of the fuel for the KLT-40S reactor was provided by Rosatom in 2006 (43):

“the [degree of] enrichment of uranium in fuel for such floating NPPs is less than 20 per cent, which meets the IAEA's [International Atomic Energy Agency] requirements on non-proliferation and ensures the possibility of export use of such plants by Russia.

Given that the KLT-40S is being developed as part of a commercially oriented concept involving potential transport to other countries it would appear logical to assume that enrichment levels in accordance with international regulations regarding non-proliferation would be adhered to ensure commercial viability. As of 2008, it appears that there is little doubt that the most probable fuel enrichment level in the KLT-40S design will be 20% or less. Vatulin et al. (44) provide information as to a potential reactor core fuel cassette system for the KLT-40S and the described system is of 121 fuel assemblies, each fuel element being 6.2 mm in diameter.

The total quantity of fuel elements in the core is 12342 (102 per assembly), the uranium density being 4.5 g/cm³. The authors indicate that testing of similar fuel elements (described technically by Svachenko (42)) in the reactor of the *Yamal* nuclear icebreaker began in January 2002 and proceeded satisfactorily. As of June 2003, Vatulin et al (44) reports that maximum build-up of fission products in the fuel elements corresponds to 0.65 g/cm³. This description constitutes the most probable type of fuel to be used in the KLT-40S. For the ABV-6M design, fuel enrichment is 16.5% as opposed to 20% for the other reactors in the series ABV series. Fuel enrichment in the VBER design is 5% with burn rates of 50 MWd/kgU and approximately 50% of that value for the VBER-150 variant.

2.4 Reactor safety systems

The interest in LCNPP's and their application has necessitated some interest in their safety features and a full and thorough discussion of general safety aspects (which include the designs being discussed here) can be found in the IAEA-TECDOC-1451 (45).

The safety systems of the KLT-40S and the majority of the other designs are designed according to six distinct principles:

- Intrinsic properties of the reactor design,
- Provision of physical in-depth protection using successive systems of protection and containment,
- Physically separate active and passive safety systems which can be activated by self-actuators without personnel intervention,
- High reliability self-diagnostic automatic systems for operator support,
- Diagnostics for reliable assessment of state of equipment and systems,

- Provision of methods for the facilitation of severe accident control.

According to these principles, the KLT-40S FNPP design features a number of safety systems that are well described by Beliaev and Polunichev (35) in a relatively thorough detailing of the systems implemented to ensure the safety of the design and the following details are drawn from that document.

The KLT-40S is described as being a pressurised water reactor design with intrinsic safety due to core feedback, the thermal inertia of the reactor itself and natural coolant circulation under emergency conditions. The reactor has a series of physical barriers and systems designed to reduce the possibilities of dispersal of radioactivity from the reactor compartment. Containment of the reactor system and fuel elements is achieved by a number of systems. The first containment system for the fuel is the fuel matrix itself followed by the fuel cladding. This is followed by a primary circuit boundary and the main containment system, surrounded by a protective barrier (32). The containment vessel itself is designed to withstand internal pressure of 0.5 MPa (0.94 MPa external pressures), during operation an internal pressure of 300 Pa is maintained. No seawater is present inside the containment vessel. The containment itself contains a variety of man-holes and access ports designed to be leak proof, all conduit and piping going into the containment are self isolating. The reactor is described as being protected against internal and external collisions or impacts. Independently functioning safety systems are built into the designs that are non-reliant on either external power or the intervention of personnel. The reactor is also described as featuring technology designed to minimise the formation of LRW during operation. The trip system for KLT-40S consists of four independently operating safety rod groupings each having their own drive mechanisms which function under a spring driven passive action. Five

independent compensating groups are present each having their own mechanism which can result in insertion of the groups to the reactor under gravity or by an electrically motor system for fast insertion. A liquid absorber injection system also appears to be provided and it can be assumed that the absorber is either borated water, boron nitride or a cadmium nitrate solution. The lowering of the compensating groups can be automatically activated by increasing pressure in the primary circuit, presumably as a result of a failure in the primary circuit pump systems.

The reactor can be cooled in an emergency situation by transfer of heat through the primary circuit through a third circuit system whereby heat is transferred to ambient temperature seawater, presumably external to the vessel/reactor. Heat removal from the reactor compartment can also be achieved by the steam generators with heat removed to either ambient seawater or via a cool down train with heat being transferred to a cool down water container and then evaporation water from this tank with transfer of heat to the atmosphere. All these systems can be control activated or via automatic systems triggered by modifying process parameters such as primary circuit pressure. The reactor compartment itself is designed to retain enough water to maintain the reactor in a safe state for a minimum of one day without any intervention from the plant operators. This is achieved by a two-system setup whereby water is maintained in the compartment using active pumps and reservoirs using one system and a second system utilises recirculation pumps to feed condensate water back into the reactor compartment,

As well as cooling of the reactor compartment an important aspect of safety design is related to pressure reduction in the reactor compartment. For the KLT-40S pressure reduction in the compartment is achieved in emergency situations by passive systems. Steam condensation is an important part of this design and surfaces for this condensation are

provided on the heat exchangers and the containments walls as well as condensation taking place in the bubbling tank of the reactor. In the event of a loss of coolant incident and overheating of the core itself and danger of meltdown, water and condensate are returned to the reactor vessel from the bubbling tank and condensator collectors. The action of condensation and feedback of water to the vessel results in pressure reduction in the reactor compartment.

A number of systems are in place to prevent damage to the containment itself in the event of a severe accident resulting in loss of the FNPP. These systems are designed to prevent the meltdown of the core and to maintain the containment integrity. The reactor exhibits negative reactivity coefficients which provide for self termination of the nuclear chain reaction once the reactor exhibits uncontrolled temperature or power elevations. Passive systems such as the EP and CG controls and design features that limit loss of coolant also contribute to eliminate risks associated with loss of control of the reactor. The inclusion of self-actuating valves in the containment and the pressure characteristics of the reactor compartment ensure that the containment is not crushed as it sinks.

Although the above text only refers to the KLT variant, all the reactors (VBER and ABV) feature essentially the same systems as they have been developed as small reactors. Deviations only appear to occur with respect to containment vessel dimensions due to the differing sizes of the reactors themselves, changes in the fuel matrix etc.

2.5 Spent nuclear fuel and radioactive waste

The general idea regarding FNPP's appears to be to leave the site as "green field" is so far as the concept can be applied to the sea, with no radiological evidence remaining as to the plant having been at its location. Four concepts

relating to how nuclear fuel and wastes can be handled in relation to LCNPP's/FNPP's have been discussed in various sources. These can be distilled down to:

- The lifetime of the reactor core is commensurate with the lifetime of the plant itself. In this scenario, the plant is decommissioned after the lifetime of the reactor and SNF is removed during decommissioning.
- The lifetime of the reactor core is equal to the period between return to base services. In this case, each time the plant is returned to base for a periodic overhaul, the reactor is refuelled and SNF is removed during the service. This scenario has been proposed in relation to plants using ABV and ABV-6M reactors.
- The third option is the use of service ships that provide fresh fuel and remove SNF from the reactor without it having to return to base and one service ship can service many FNPP's. This is essentially the system used currently on the civilian icebreaker fleet.
- The final option envisages an FNPP with integrated SNF storage facilities whereby fresh fuel is stored on the FNPP, refuelling occurs without return to base operations and the SNF is stored on the FNPP. A number of refuelling cycles can be completed before return to base for service and SNF removal. This is the option to be implemented for the KLT-40S design being constructed at Severodvinsk.

The best available information as to the design of the FNPP currently under construction indicates that, located near the reactor compartment itself, facilities are provided for spent nuclear fuel (SNF) and where SRW and LRW may be handled and stored. These facilities (of dimensions 7 m x 7 m x 9 m) are also stated to allow for the handling for fresh

nuclear fuel and for refueling operations. Furthermore, explicit indications and statements can be found in IAEA-TECDOC-1172 (p. 6 of (46)) that both SNF and radioactive wastes are to be stored and handled onboard the FNPP's:

“Spent fuel and radioactive waste are stored on board the FNPP. Thus, the autonomous operation period (operation without supplies replenishment) of the FNPP is determined by the capacity of spent fuel storage. The autonomous operation of the FNPP is ensured by four nuclear core sets and lasts ~15 years. After the lapse of this period the FNPP is to be towed to the dock for overhaul, fuel unloading and hull docking. Two overhauls and three operating cycles are planned. After the completion of the third cycle the FNPP is to be towed from the site to the premises of the specialized dock for decommissioning.”

Radioactive waste is described as being able to be handled by wet storage in three leak proof storage tanks allowing for dissipation of residual heat from spent fuel assemblies and subsequent storage in one of four tanks with air cooling. Handling of LRW is by means of an engineering system designed to accumulate liquid wastes from reactor plant operations, radioactive water from the metal-water shielding as well as facilities for the temporary storage of LRW and for its transfer to support ships or coastal facilities during factory servicing. If information derived from IAEA documents is assumed to be the most authoritative, it must be assumed that some handling and storage of radioactive wastes will be conducted on board the FNPP.

The more authoritative sources of information indicate that refueling of the reactors will occur every three to four years (consistent with an enrichment level of ca. 20% ²³⁵U) with the plant being returned for service and removal of SNF and wastes every 10 to 12 years. Assuming two loads of SNF to be stored on the vessel. The best indication of generated waste volumes for the KLT-40S design in an FNPP is provided by Beliaev and Polunichev (35). For

one reactor (two being present on each FNPP), the annual generation of waste is given as 8 m³ of LRW and 2.5 m³ of SRW. For two reactors therefore and assuming that 10 years waste will be stored on the FNPP between return-to-base services, the total volume of LRW would be 160 m³ and 50 m³ of SRW. The LRW is stated as being expected to have an average activity of the order of 0.37 MBq/kg (10⁻⁶ Ci/kg) which would, assuming a density of 1000 kg/m³, a total activity of the order of 60 GBq for LRW. 70% of the SRW is expected to have an activity of the order of 0.37 MBq/kg that implies a lower estimate for total activity for SRW over the same time period of some 13 GBq. A total estimate of the order 73 GBq total waste activity would therefore appear to be a very conservative estimate with respect to both the activity of the generated wastes, the volume generated and the overall period during which the waste is generated. It should of course be understood that this waste inventory is in addition to the storage/presence of 12 years worth of irradiated nuclear fuel, assuming that SNF is stored on board between returns to base, a conservative estimate being of the order of 10 t of SNF.

With respect to the larger overall picture of nuclear waste handling, Shadrin and Kuz'min (47) describe the volume of waste (pressed, in the dry state). Although the waste volumes likely to be generated by FNPP operation appear quite small, the SNF that will (according to a number of sources) be stored on board the FNPP constitutes a more significant potential source term of radioactivity in terms of amounts. The inventory of radioactivity in the core of a reactor consists of radioactive noble gasses (isotopes of I, Kr etc), fission products (such as isotopes of Cs, Sr, etc), transuranics (isotopes of Pu, Np etc) and other species such as activation products in cladding or reactor materials etc. The primary groups of concern from a pollution point of view are the fission products and transuranics as the noble gas isotopes and activation products tend to have short half-lives and decay away quite quickly. The amount of fission products produced in a

reactor depends largely on the amount of ^{235}U that has undergone in the reactor that is related to the burn-up of the reactor. The amount of transuranics produced in the reactor is dependant on the burn-up, the initial level of enrichment of the fuel and the design of the reactor. Without detailed knowledge of the amounts of ^{235}U in the reactor, reactor design and operational parameters, an apriori evaluation of the inventory of potential SNF is impossible to derive. However insight into the orders of magnitude of radioactive isotopes in SNF from and FNPP is provided by Reistad and Olgaard (48). For the Sevморput reactor for example, assumed to consist of approx 200 kg of uranium with 90% enrichment having a burn-up of 78000 MWd, fission products such as ^{137}Cs and ^{90}Sr have activities of the order of 10^{16} upon shut down and transuranics such as ^{241}Am and ^{240}Pu are present in amounts between 10^{11} and 10^{14} Bq. Such nuclides as Pu isotopes and fission products such as those mentioned have relatively long half-lives and will not diminish appreciably over the 8 – 9 years holding time for SNF as predicted by available information as to FNPP's. These values are at best a rough approximation but serve to demonstrate the significant amounts of activity present in SNF and that irrespective of the projected small amounts of waste, significantly large amounts of radioactivity will be present on board an FNPP for significant periods of time between return to base services.

It should be noted that not all FNPP designs include waste or SNF storage in that they are designed such that the period between return to base services is equal to that of the reactor life time and thus fuel can be removed at a dedicate facility. This refers in particular to the ABV-6M and VBER-150 variants. Referring to the ABV-6M design, Kostin et al (36) state:

“enhanced environmental safety of the reactor is provided by the principle ‘Neither spent fuel nor rad-waste onboard’”

and that refuelling is expected every 10 to 12 years and is to be conducted at specialised shore facilities.

2.6 Availability of information

Quite extensive information is available as to technical details of proposed FNNP's, LCNPP's and implementations of both to desalination, process heat provision and domestic heat and electricity supply. This information is available for the period between the early to mid 1990's. The types of information available include extensive design information as to safety systems, designs of reactors, technical and operational details, schematics of reactors, fuel elements, reactors with ancillary systems, details as to steam generators, etc. The information is presented primarily via the publications produced as results of Co-ordinated Research Projects run by the IAEA, through presentations at relevant conferences and through, primarily, the Russian literature although translations of some of this literature are readily available. The following publications can be considered as reliable, freely available, up to date sources and contain extensive information describing developments and technical details as well providing some insight into how these technologies may develop themselves commercially:

- IAEA-TECDOC-1536 (Status of Small Reactor Designs Without On-Site Refuelling) 2007
- IAEA-TECDOC-1326 (Status of design concepts of nuclear desalination plants) 2002
- IAEA-TECDOC-1391 (Status of advanced light water reactor designs) 2004
- IAEA-TECDOC-940 (Floating Nuclear Energy Plants for Seawater Desalination) 1997
- IAEA-TECDOC-1451 (Innovative Small and Medium Sized Reactors:

2.7 Main points

- Some FNPP designs include SNF and waste handling facilities on board, being designed to cater for the materials generated over the period between return to base services which involve storing 3 refuelling cycles worth of SNF and wastes.
- Detail as to the volumes of waste generated and storage/handling procedures are limited.
- Not all FNPP's store SNF/waste, some being designed to be only refuelled at base at which time SNF and waste is removed.

3 Details regarding nuclear powered desalination plants

Although it would appear unlikely that a large number of nuclear powered desalination plants would be operative in the Arctic region, the development of an industry related to this technology in the Arctic, from where such plants would be dispatched and to where they would be returned, confers relevance to the topic. A number of basic designs for Russian proposed nuclear desalination plants are in evidence. The first of these is as described by Kostin et al. (21) and is based on the KLT-40S concept for FNPP's. In a similar manner to FNPP design, the nuclear power desalination plant consists of a floating nuclear power supply unit and a coastal infrastructure component. The floating plant is integrated with a desalination complex. Although KLT-40S reactor systems feature prominently in descriptions of Russian desalination plants, a second design has also been described in IAEA-TECDOC-1561 (19) and this is based around the use of an RITM-200 reactor. The RITM-200 is a PWR reactor with forced primary coolant circuitry generating 210

MW(e) with a higher steam generating capacity than the KLT-40S and similar to the KLT-40S in other relevant parameters. Whilst the KLT-40S is a finalised design, the RITM-200 appears to be, as of 2007, a conceptual design and less information is therefore available. It should be noted that although the KLT-40S are to be installed in pairs, nuclear powered desalination plants based on the RITM-200 design will contain one reactor. Russia has some experience in the operation of desalination facilities through their use on existing nuclear powered vessels in the Russian fleet. Two distillation design types have been in use: the M4C1 and the M3C used on "Arktika" class icebreakers and "Taimyr" class (including *Sevmorput*) vessels and producing 120 m³ and 60 m³ of potable water per day respectively. However, the scale of operations on these vessels is much smaller than would be required for a marketable solution for cities or states and Russia has entered into a joint development project with the Canadian CANDESAL company who will provide the desalination technology to be powered by the Russian FNPP's. Humphries and Davies (49) describe the basis of the integration between the Canadian desalination system and the Russian FNPP. The power unit is as described before and the FNPP occupies its own barge. The desalination unit occupies a second barge. The desalination system can be one of either two designs – Reverse Osmosis (RO) or Multi Effect Desalination (MED). The two barge design for the RO system (the MED system appears to use a single barge design) means that the FNPP can be separated from the desalination plant and the authors provide the following advantages to the system:

- Possibility of manufacturing of the power plant in the supplier country;
- High fabrication quality and "turn key" delivery;
- Ease of redeployment;
- Convenient maintenance and refuelling at the supplier's country.

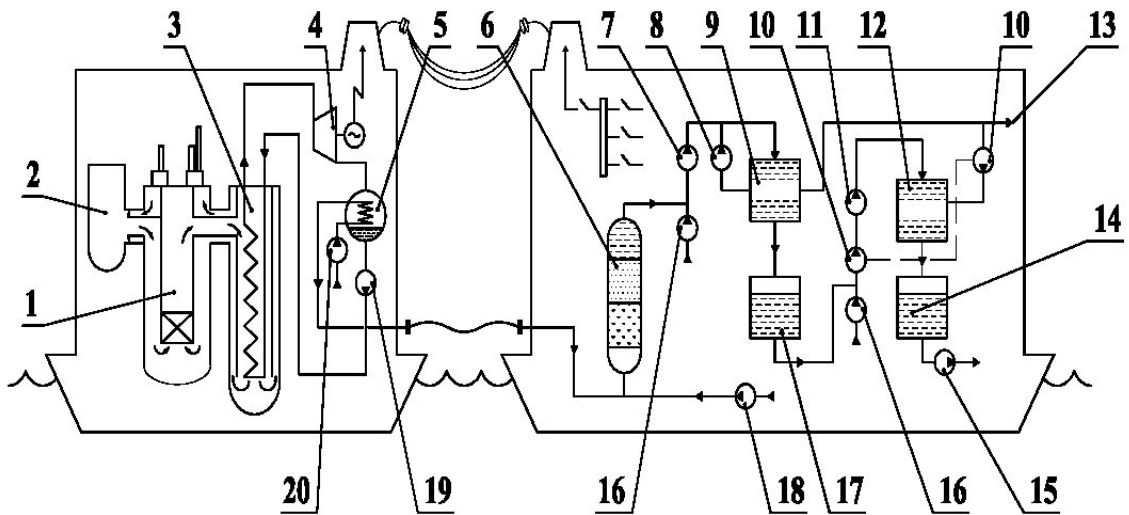


Figure 11 . Schematic of a KLT-40S FNPP and RO desalination unit. 1 – KLT-40S reactor, 2 – primary circuit pump, 3 – steam generator, 4 – turbo generator, 5 – condenser, 6 – prefilter, 7 – pressure pump, 8 – recycling pump, 9 - ultra filtration membrane, 10 – energy recovery unit, 11 – high pressure pump, 12 – RO membranes, 13 – outflow structure, 14 – fresh water storage, 15 – fresh water pump, 16 – injection system, 17 – clarified water storage, 18 – pump, 19 – secondary circuit pump, 20 – pump (source: IAEA-TECDOC-1326 (23)).

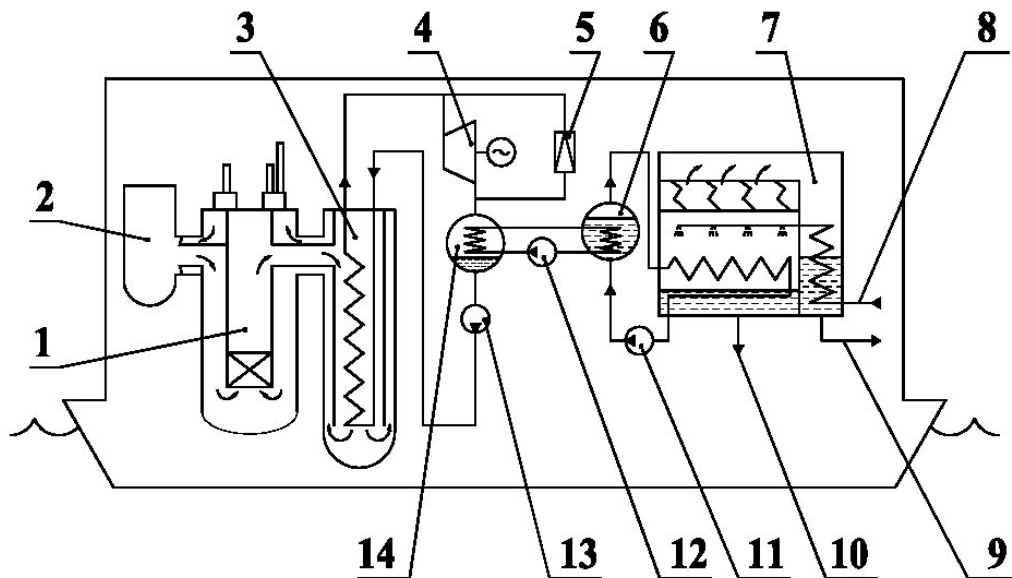


Figure 12 . Schematic of a KLT-40S FNPP and MED desalination unit. 1 – KLT-40S reactor, 2 – primary circuit pump, 3 – steam generator, 4 – turbo generator, 5 – reduction cooling set, 6 – steam generator, 7 – distillation desalination plant, 8 – seawater inlet, 9 – evaporated seawater brine concentrate outlet, 11 – pump, 12 – intermediate circuit pump, 13 – secondary circuit pump, 14 – condenser. (source: IAEA-TECDOC-1326 (23)).

The desalination barge is to be a non-propelled barge, approx. 96 m in length and 28 m wide, serving to house the desalination system, provide salt water supply to the system, pre-treatment of the water, supply of freshwater to the shore based station and cleaning of the desalination units. Cooling condenser water from the FNPP's cooling system is used as feed water for the RO system, in the MED system waste heat from the reactor is used in the distillation process. Technical descriptions of the desalination plant are provided in figures 11 and 12.

3.1 Safety and environmental aspects of nuclear powered desalination facilities

For the environment of the Northern areas, the primary risk associated with the concept of nuclear powered desalination plants is related to their manufacture and servicing/decommissioning at, presumably, sites in the Northern regions and related transport. However there have been indications that a small number of these plants could be operational in the Arctic or related areas and it is therefore worth briefly discussing some safety and environmental aspects.

As for any nuclear plant, floating or otherwise, the primary safety aspect or concern for a nuclear desalination plant is due to possible accidental releases of radioactive materials to the wider environment. Specific to the operation of nuclear desalination plants however is a concern with respect to the potential for discharge of radioactivity via the produced fresh water as well as the environment with subsequent effects on the biosphere and human health. The precautions to prevent release of radioactivity from a nuclear powered desalination plant are the same as those for FNPP's or other power plants. Prevention of radioactive contamination of produced freshwater can be achieved by engineering features such as barriers and pressure differentials to ensure that contamination does not reach the produced

water stream. Obviously, stringent monitoring and control of produced water is required to ensure the safety of the product and the consumer's confidence in it.

While the safety of a nuclear reactor or an FNPP can be assessed according to well defined systems, the coupling of reactor to a desalination plant necessitates the consideration of an extra set of systems. In connecting an FNPP with a distillation system such as MED, a direct exchange of heat must be accomplished and this involves a thermal coupling between the FNPP and the desalination plant. Transient power fluctuations in either the FNPP or the desalination plant can potentially have an effect on the functioning of the other system and the effect of such transients in one system on the other need to be evaluated and assessed. In an FNPP desalination plant the desalination facility functions as the heat sink for the FNPP. The balancing of the operations of the two with respect to safety is a factor requiring assessment. A failure in the desalination plant could result in problems for the FNPP as the ability to remove heat from the reactor can be compromised. For FNPP's connected to RO systems, the coupling is weaker than for an MED or other distillation system due to the RO system only drawing electrical power from the FNPP. For an RO unit drawing its feedwater from the reactor systems, failure in the RO unit is unlikely to cause problems for the FNPP. The environmental effects of an FNPP powered desalination facility are unlikely to be any more significant than for an FNPP nor is the risk any higher. Any radiological effects or the risk thereof will most likely be dwarfed by the potential environmental effects of thermal discharge and the brine waste product of the desalination process.

3.2 Main points

- Desalination is an important area for the implementation of FNPP technology and is the subject of significant attention from a number of

countries and agencies. The need for and interest in nuclear powered desalination, for which FNPP's offer advantages, is only likely to increase in coming years.

- Russia has developed FNPP desalination systems in collaboration with other countries and is marketing these systems internationally.
- The coupling of FNPP's and desalination systems is technologically feasible and presents no major challenges.
- The radiological environmental impact of FNPP powered desalination is significantly greater than for operation of an FNPP alone.

4 Environmental and risk assessments

The primary concern in relation to the presence or transport of FNPP's and related technology through the Northern Regions is the risk posed to human health and the environment as a result of regular operation or an accident involving such facilities with discharge of radioactivity to the wider environment. As control of risk is largely achieved through regulation and legal requirements, it is worth summarising international agreements and instruments pertinent to the concept of FNPP's or related facilities.

4.1 International conventions regarding nuclear materials at sea

The concept of FNPP's will, as with most aspects of nuclear power, engender varying levels of opposition from various groups/organisations and some of these protests will undoubtedly focus on legal aspects and international conventions. It is therefore useful to present a brief overview of the type of conventions that may be applicable to FNPP's

4.1.1 Background to FNPP's in the international legal context

FNPP's were the subject of discussion regarding maritime law shortly after Offshore Power Systems announced plans for the building of FNPP's off the coast of the United States in the 1970's. FNPP's first made their appearance on the international legal stage at the United Nations Conference on the Law of the Sea in Caracas in 1974 (50) at which FNPP's appeared under the topic:

“Artificial offshore islands, facilities or similar devices other than those which are mobile in their normal mode of operation at sea”.

The discussions focussed on FNPP's in the territorial zones and upon the high seas (which included the economic zone). Certain themes are still of relevance today and are therefore worth listing:

- The right of a State to construct FNPP's in its territorial waters only where the presence of the facility does not hinder access to a neighbouring states ports or damage the marine environment of the territorial waters of neighbouring states,
- The publication of plans to build FNPP's in territorial waters and take into account neighbouring states considerations,
- Construction of FNPP's in the economic zone need only pay heed to freedom of shipping and fishing,
- Differences were established between FNPP's attached to the shore or continental shelf and those for the exploitation of natural resources out to sea.

From the first discussions of FNPP's position with respect to international maritime law, it was clear that they occupied a difficult position characterised by a lack of clarity and their position was not further elaborated upon once the concept was dropped as a viable

proposition whereas nuclear maritime transport and radioactive waste dumping proceeded to be developed within legal regimes over the years.

4.1.2 FNPP's in the current international legal context

FNPP's Considering FNPP's and their operation and transport to be situations involving maritime transport of nuclear materials, a number of frameworks and treaties appear to be relevant. The Basel Convention of 1989 on the Control of Hazardous Wastes and Their Disposal is the main international system regarding transport of hazardous wastes but does not include radioactive wastes. However a large number of other agreements and instruments relating to nuclear materials and their transport may be or definitely are applicable to the, for example, the movement of nuclear materials by ship, operation of FNPP's or other technologies at sea etc. Of the legal systems that exist, 5 are of apparent specific relevance to the subject of the operation or transport of FNPP's and associated technologies

The role of states in regulating the movement of nuclear shipments is addressed by the IAEA "*Code of Practice on the International Transboundary Movement of Radioactive Waste*" although this code has no binding legal status and serves only as an advisory or recommendatory system. Irrespective of that fact, the Code does have acceptance as setting international standards and some of its recommendations may be covered by other agreements. How vessels involved in nuclear transportation are built, equipped and operated is described by the International Maritime Organisation's (IMO) "*International Code for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High-level Radioactive Wastes on Board Ships*" of 1993 which is now known as the INF Code.

The INF Code covers all new and existing ships irrespective of tonnage that are involved in the transportation of INF Code materials. Three classes of vessels are defined in relation to the total maximum amount of radioactivity that may be carried. The lowest class is Class INF 1 vessels and the highest class are Class INF 3 vessels.

- Vessels certified to transport total activities < 4000 TBq are Class 1 INF vessels.
- Vessels certified to transport irradiated nuclear fuel or high level wastes of total activity $< 2 \times 10^6$ TBq or Pu of total activity less than 2×10^5 TBq are classified as a Class INF 2 vessels.
- Vessels certified to transport irradiated nuclear fuel or high level wastes or Pu of unrestricted activity are Class INF 3 vessels.

The INF Code details requirements regarding vessel design, equipment damage stability, fire protection, thermal control of stowage, structural considerations, etc for each class of vessel. The Code also describes requirements for radiological protection equipment, management plan, and emergency plans. Adherence to the INF Code is voluntary although some countries have made it mandatory and the European Union is taking steps in that direction and the IMO was to have made the INF code mandatory by 2002.

According to the regulations as outlined above, radioactive materials are transported in specific container specifications. Type A containers protect and retain contents under what can be considered normal transport conditions and maintain adequate shielding to limit radiation exposure to handling personnel. Type B containers are for transporting materials with radioactivity levels higher than those in Type A containers and retain their contents under both normal and severe accident conditions, ranging from steel drums of 200 litres to shielded steel containers up to 125 t. Type B

containers contain materials such as irradiated nuclear fuel, high-level radioactive waste and plutonium. Shipping using Type B containers in international trade requires the shipper to have a “certificate of competent authority” from the appropriate country or countries. Once obtained, the shipper must ensure that the packaging and its contents meet the applicable requirements of the certificate.

Transportation of packaged radioactive material can occur via container vessels, roll-on/roll-off vessels, general cargo (break-bulk) vessels, or purpose built vessels. The preferred method of commercial transport of Type B containers aboard vessels is mounting of the containers in so-called “International Standards Organization (ISO) containers.” Type B containers in ISO containers are usually transported on general cargo vessels rather than on large container vessels specifically designed for container transport. Individual shipments can be made by scheduled commercial vessels, or by charter vessels. Purpose-built vessels are designed to transport Type B containers containing large quantities of radioactive material, and operate as dedicated vessels. A vessel transporting radioactive material must comply with the requirements of *the International Convention for Safety of Life at Sea (SOLAS)* to which the vessels flag state is a party and must also adhere to the IMDG Code. Also, vessels transporting INF Code materials should also voluntarily comply with the Resolution A 748 (18), the *Code for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High-level Radioactive Wastes in Flasks On Board Ships* as adopted by the IMO in 1993.

The IMO also publishes standards for the transport of hazardous materials and in this regard the *International Maritime Dangerous Goods Code (IMDG)* includes radioactive material and establishes standards for shipping documents, marking, labelling, signage, stowage, segregation of materials and handling requirements. The IMDG Code incorporates IAEA standards for certain aspects. The IMO

in liaison with IAEA established the *Code for Safe Carriage of Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes in Flasks on Board Ships* which supplemented the IMDG Code in relation to the provision for requirements as to ship design and construction and established international criteria for vessels transporting certain high activity radioactive material, such as irradiated nuclear fuel, high level waste and plutonium which are generally designated as the previously mentioned “INF Code” materials. The IAEA have also issued the *Regulations for the Safe Transport of Radioactive Material* since 1961 and as of today the latest edition is identified as IAEA Safety Standards Series No. ST-1 of 1996. The Regulations are based essentially on the *Basic Safety Standards for Radiation Protection Against Ionising Radiation and for the Safety of Radiation Sources, Safety Series 115* as published by the IAEA and taking into account such recommendations as made by the International Commission on Radiological Protection (ICRP). The IAEA Regulations constitute a regulatory system that specifies standards for the preparation of containers for transport by sea: proper selection of containers, marking and labelling, and container/vessel marking. The system also includes segregation and stowage guidelines for shipping. Containers must be segregated from transport workers and members of the public. Stowage spacing is determined by the container surface activity or by criticality risk. Stowage requirements ensure that packages are not placed in holds containing other hazardous goods (such as flammable materials). The Regulations also describe quality assurance systems for the design, manufacturing, testing, documentation, employment, maintenance, and inspection of containers. Some 40 countries that are active in the transportation of nuclear materials are also signatories to *The Convention on the Physical Protection of Nuclear Material* (published by the IAEA INFCIRC/274/Rev.1) and most countries also follow IAEA guidelines and recommendations (published as IAEA’s INFCIRC/225/Rev.2, *The Physical Protection of Nuclear Materials* (51) for the protection of nuclear materials

during transport. Documentation related to the transport of nuclear materials and the requirement to observe the precautionary measures established by relevant international agreements is covered by the United Nations Convention on Law of the Sea (UNCLOS) of 1982. All these relevant codes and instruments have differing legal statuses. The IAEA Regulations covering how such materials should be packaged are encouraged for adoption in national regulations whereas the INF Code is mandatory for all civilian ships that carry irradiated nuclear fuel cargoes.

Publication of the IAEA Code in 1990 provided the following of reference to FNPP's and associated transport:

- States should exercise their rights to regulate movement of radioactive waste into, from or through their territories,
- States engaging in transboundary transportation of radioactive wastes should ensure prior notification and obtain consent of the sending, receiving and transit states,
- States that have wastes transferred from them in a manner non-compliant with the code should accept the return of the wastes,
- States should collaborate to prevent movement of radioactive wastes in contravention of the requirements of the code.

Also relevant to the concept of FNPP's are the INF Code in so far as it relates to the design, construction and operation of vessels carrying INF material and high-level wastes and it is mandatory in 2001 via amendments to the International Convention for the Safety of Life at Sea (SOLAS). The IMO IMDG Code, based upon the IAEA Regulation became mandatory in 2004 via amendments to the same chapter (Chapter VII, Carriage of Dangerous Goods) of SOLAS. Some sections of the IMDG are recommendatory only especially in relation to Class 7 radioactive materials.

The IAEA Regulations, concerned with packaging of radioactive materials for transport, set out standards for the performance under a number of criteria of different classes of packages or containers for transporting radioactive materials as described earlier. These regulations set international standards and IAEA Member States are encouraged to adopt the regulations in their national regulations. A range of organisations have regulations or agreements or relevance to the concept of FNPP's and their transport of varying applicability and enforceability. The IAEA continues to develop the concept of states obligation to protect the marine environment but a comprehensive and binding legal framework has yet to be developed.

Despite the existence of a range of instruments and agreements, disputes can and do arise in relation to the transport of nuclear materials from one state through the marine territory of another. In 2004, the US ran into problems in trying to transport a decommissioned reactor between California and South Carolina by sea largely due to the national regulations of countries through whose waters the transport would have to pass. In particular, Chilean nuclear safety laws including clauses pertaining to the requirement of guarantees from the shipper to keep the environment free from contamination posed problems for the shipment. Argentina passed a law immediately before the shipment which warned that military interception of the vessel would take place should the vessel enter Argentinean waters and it would be escorted out of its territory. Disputes have arisen as a result of plutonium shipments between facilities in western Europe and Japan with countries such as South Africa and Portugal "requesting" that ships of the British nuclear fleet stay out of their territorial waters, *Pacific Pintail* being specifically banned from the waters of Brazil, Argentina, Chile, South Africa and Kiribati whilst trying to ship vitrified high level waste to Japan and the same shipment resulted in the deployment by Chile of military aircraft and vessels. Strident disputes have arisen between the

United Kingdom and the Republic of Ireland over the years due to shipments of nuclear material from the United Kingdom ranging from official complaints to hints of naval responses should such vessels enter the latter's territorial waters. The general situation regarding regulation and international rules and laws that may pertain to FNPP's, their operation, their transport and their commercial exploitation is complex and far from clear. The commercial model under which all indications are that they will be marketed ("*Build-Own-Operate*") or a form of leasing has already come under scrutiny internationally as it is not just Russia that has focussed on the concept and as has been noted, the model is the product of international and national movements towards reforming the global nuclear business. Beaufoy (52) discusses the situation from Australia's point of view (another nation looking at leasing as a solution regarding Australia's export of nuclear materials) and his two of his conclusions form a concise summation of the situation:

- *"If the nuclear industry is set to grow on a global scale and nuclear leasing forms a part of the nuclear fuel cycle world-wide and nuclear shipments increase, greater coordination, consistency and transparency will be required in the international laws which apply to this industry at sea",*
- *"The unilateral actions by various states in relation to the shipment of nuclear waste,, as well as regional examples of bilateral and multilateral agreements, should be sufficient impetus to promote a concerted international response to this issue; rather than waiting for the break up of a nuclear cargo ship at sea".*

It therefore appears that extant systems of international regulation and the agreements under which such systems are implemented may not be sufficient to deal with the new

challenges posed by, generally, new commercial models regarding nuclear technology, and in particular, the situation posed by FNPP's and their commercialisation.

4.2 Earlier American environmental assessments

Significant amounts of material are available from assessments and analyses performed in the 1970's and early 1980's during the period when the United States were actively developing such systems. Access to such information is complicated slightly by the age of the material and the publications in which such information was disseminated (primarily industrial and governmental reports). Problems also exist in that such assessments were conducted at a time when priorities with respect to radiological protection were significantly different to currently adopted concepts in a number of ways, particularly with respect to protection of the environment, and as such assessments as conducted were for locations and reactor designs/power not necessarily pertinent to the situation of today.

A relevant distillation of the state of knowledge regarding environmental and risk assessment of FNPP's conducted at the time is that reported upon by OTA (53). Major findings of this assessment included that (for the designs existing at the time) the risk of a most severe accident (ie. a core meltdown) was no greater for a FNPP than for land-based facilities of the time. The report also concluded that the probability of atmospheric releases of radioactive materials was approximately 7 times greater for the FNPP design considered than for a land based plant but that the offshore location of the plant may mitigate the consequences of atmospheric releases due to the plant being far removed from population centres. However in the event of a core meltdown, potential interaction of the core with seawater could produce atmospheric releases that could not be included in assessments of accidents for equivalent land based plants. The OTA report also identified

deficiencies in technical details regarding fuel and waste handling on board FNPP's but this was determined to be a weakness in relation to planning as opposed to a lack of engineering development.

The extent to which assessments conducted almost 40 years ago for different plant designs and locations can be applied to current plans is limited. Reactor safety has increased in the last decades and new technologies and the experience of 4 decades (including accidents and incidents) has improved the situation with respect to the reliable operation of all types of nuclear facilities. Assessments from the 1970's were also conducted with respect to much larger capacity reactors and the planned designs of today are significantly smaller. It should therefore be assumed that little information can be gained from analysis of such assessments and more recent material should be taken into account when trying to assess potential environmental impacts.

4.3 Relevant Norwegian environmental assessments

Assessments of previous accidents or scenarios involving nuclear powered vessels in the northern regions are limited. A relevant scenario analysis however is that conducted by Iospje et al (54) in which the radioecological consequences of an accident involving the transport of SNF along the Norwegian coast was studied with respect to environmental impacts. This study was conducted in order to assess the potential consequences arising from an accident in Norwegian waters involving a ship carrying SNF. While the fuel enrichment values, burn up rates and composition may be such that inference could be drawn to, for example, loss of a FNPP at sea, it is likely that the amount of SNF involved in this assessment was greater than that which would be found on intended designs for FNPP's. Bearing that in mind however, plans for international use of FNPP's and the potential for transport of SNF and wastes to the provider (ie. Russia) mean that future years

could bear witness to the type of accident as described by this analysis. Results provided by Iospje (54) indicate that an accident involving the loss of SNF near the Norwegian Coast can have significant consequences with respect to intervention levels for levels of certain isotopes in certain types of foods over significant periods of time. However doses delivered to man as a result of the modelled accident do not exceed background in any instance. The economical impacts of such an accident are not however difficult to imagine and impose a certain gravity on the potential transport of materials near or through Norwegian waters as a result of FNPP use in countries outside of Russia under the most likely commercial model.

A study involving the loss of the nuclear submarine "*Kursk*" in 2000 (55) is potentially useful as the input reactor model (assuming two reactors in the submarine) was based upon the *Sevmorput* KLT-40 reactor and therefore is potentially more relevant for attempting to elucidate the consequences of, for example, loss of an FNPP of the currently being constructed design at sea. Weaknesses in using the *Kursk* analysis are obviously related to the fact that even though the *Sevmorput* reactor model is similar to that of the KLT-40S reactor design of FNPP's, the specificities of fuel design, burn up rate (and therefore fission product inventory), ²³⁵U enrichment, fuel element construction etc. may not be and these are factors of potential significance. The "*Kursk*" analysis was concerned primarily with two scenarios, the first involving instantaneous release of 100% of the total reactor inventory during an accident upon the raising operations (see Table 3 for details). As this is relatively hard to visualise for operations involving an FNPP, the second scenario is potentially more relevant. This involved release from the reactor over time having assumed that seawater penetrated the reactor containment at the time of sinking, primary circuit pipework having been damaged as a result of the accident and that seawater had penetrated the reactors pressure vessel. The scenario goes on to assume that the fuel cladding, 100% intact at

the time of the accident, corrodes away totally in a period of 100 years. It should be noted that the

likelihood of a sequence of events occurring that would compromise all safety features and produce conditions amenable to rapid corrosion of the cladding and fuel matrix would appear to be small.

	Used in model of "Kursk"		Used in model of "Kursk"
Generation	Third	Core diameter:	121.2 cm*
Max thermal power (MWt)	200 MW	Assembly:	Outer diameter. 6 cm*
U-235 (kg)	Basic: 150.7 kg* Range: 75 – 200 kg	Outer clad:	Thickness: 0.06 cm Material: Zr*
Enrichment	Basic: 30% Range: 20-90%	Inner clad:	Thickness: 0.06-0.006 cm Material: Zr*
# Fuel assemblies	241*	Number of pins/assembly	55*
Fuel composition	1) U-Al alloy foil clad in Zr tubes. 2) U-Al alloy dispersed in a matrix	Active core height:	100 cm*
Fuel geometry	Circular pins in hexagonal lattice*	Coolant flow area:	0.26 m ² *
U-235 pr. fuel assembly (kg)	Basic: 0.625 kg	Reactor burn:	12000/24000 MWd

Table 3. details of the reactor model used in post-accident analysis of the sinking of the Kursk in 2000. Source: Amundsen et al (55).

information known about the KLT-40S indicates zirconium cladding which, under normal conditions, should retain its integrity for hundreds if not thousands of years and that the fuel matrix itself appears to have been designed with resistance to seawater corrosion in mind. Secondly the containment vessel of the KLT-40S is stated to feature a number of safety mechanisms designed to prevent either ingress of seawater to the reactor or egress of radioactive materials from the core and that major components of the reactor construction itself feature "anti-corrosion" cladding or facings. Despite these features, under conditions of galvanic corrosion even zirconium can corrode within months so it is hypothetically possible that the fuel cladding of a KLT-40S can corrode and release occur under certain circumstances although the

For scenario 2 and using a burn time of 24000 MWd, the collective dose from the Barents Sea for a period of 100 years post accident amounted to 19 manSv with the main contributions arising from ¹³⁷Cs and ²³⁹Pu. Based on the Kursk analysis it is difficult to envisage a scenario involving an FNPP whereby a situation could arise of significantly higher severity than that envisaged in the Kursk analysis involving scenario 2. An aspect to consider in relation to the Kursk analysis is that FNPP's may contain SNF equivalent to 6 or more FNPP reactors as 10-12 years worth of reactor fuel are envisaged to be stored on each FNPP.

4.4 General environmental assessments of relevance

In relation to the potential long term impacts of a sunken FNPP, a broad assessment of radionuclide releases from a range of dumped reactors in the Kara Sea was conducted a number of years ago as part of the International Arctic Seas Assessment Project (IASAP) and reported in IAEA-TECDOC-938 (56). These dumped objects included six submarine reactors with spent fuel, spent fuel from an icebreaker, ten reactors without fuel and a range of liquid and solid wastes. The general conclusion of the assessment was that a criticality situation following corrosion of reactors was very low and that release rates of radioactivity from dumped objects was also very low given the measures employed prior to dumping. These conclusions reflect the situation pertaining to the Komsomolets submarine and which has exhibited very little discharge of activity. It would therefore seem unlikely that a sunken FNPP, given the development of safety measures in the years since reactors were dumped in the Kara Sea and the improvements in fuel technology and design would be likely to exhibit any greater tendency to release significant amounts of radioactivity than the dumped reactors in the Kara Sea or the reactors of the Komsomolets or Kursk submarines.

The situation regarding radioactive wastes on board an FNPP is less clear. Although it seems clear, based on previous incidents and sunken reactors and the information to hand as to the design of current and proposed FNPP reactors that an FNPP reactor within its containment would exhibit a low probability of discharging large amounts of radioactivity to the environment in the event of loss at sea, the presence of stored SNF and LRW and SRW on board is a factor that is less easily assessed. Iospje et al (54) has shown that an accident involving a vessel containing SNF can have significant consequences with respect to levels of contaminant radionuclides in marine biota. Essentially no information is available as to

storage and handling methods for SNF and radioactive wastes on board FNPP's and although waste amounts may be relatively small, given the size of the reactors, the presence of such materials on board is a cause for concern in the absence of concrete information.

FNPP's perhaps constitute a unique case for environmental assessments in relation to two aspects. The first is that they can be located in areas where nuclear vessels may not be found such as rivers and estuaries and constitute a source term not represented in assessments for shore based nuclear facilities (i.e. where nuclear fuel, fresh or used, may actually end up in the river/estuary). The potential impacts on such environments of an accident or discharge from an FNPP are difficult to quantify and therefore constitute an unknown. The same siting however means that a sunken FNPP, which constitutes a significant investment for the owner, will be most likely recovered from the shallow waters of a river, estuary or near coast environment meaning that a sunken FNPP is unlikely to present a long term risk.

However, it is well established that incidents and accidents involving nuclear power or radioactive materials can have consequences over and above those related strictly to radiological dose and the Arctic area is a region uniquely sensitive to the perception of contamination and even the possibility of radioactive contamination can have adverse consequences on a number of levels including societal and commercial.

4.5 Risk assessments

Impacts on the environment of an accident involving an FNPP can logically only occur in the event of an accident. The probability of such an accident or the releases of significant amounts of radioactivity into the wider environment are naturally of some significance and determinations of accident risk are routinely performed for land-based power

plants etc. Given that an FNPP has not actually entered service as of yet it is difficult to quantify the risks associated with their operation. It is however possible to contextualise FNPP's within the general risk picture presented by; for example, the operation of the civilian nuclear fleet or nuclear material transport by sea and to try and identify risk factors specific to FNPP's.

4.5.1 Analysis of accident risk involving transport of radioactive materials by sea

The IAEA (57) conducted risk analysis for the shipment of radioactive materials by sea within the framework of the regulations that are briefly described in the previous section. These analyses constituted a thorough and rigorous treatment regarding risks to transported materials from a variety of scenarios (fire, crush damage, collisions, etc.) utilising models, regulation specifications of transport containers, shipping statistics, accident statistics etc.

The conclusion of these analyses indicate that for plausible accidents involving shipping carrying nuclear materials in compliance with extant regulations and in standard transportation containers as specified in those regulations, crush damage to a Type B container as a result of serious hold penetration in a collision would be mitigated by collapse of the ships structure as opposed to breach of the container and that it was difficult to envisage a situation where the containment provided by such a container could be breached. Modelling of onboard fires indicated that spreading of fire to a radioactive material stowage hold is improbable and in the event of a fire reaching the hold that the fire was unlikely to attain or maintain temperatures sufficient to damage or cause leakage of radioactivity from a Type B flask. In addition, neither loss of a Type B flask to the ocean or the atmospheric dispersal of its contents as a result of a collision were determined to constitute a radiation dose to

individuals of any significance (relative to normal background dose). The overall conclusion was that for radioactive materials transported according to international regulations and codes, the risks associated with transport by sea were very small.

4.5.2 Accidental risk scenarios

Although it is possible to visualise the entire gamut of potential accident scenarios it is possible to break down the scenarios into two general groups. The first of these is damage to the vessel as a result of accident or incident whereby SNF, wastes or the entire reactor and its associated material is lost at sea. As discussed in section, situations involving loss of properly stored (in this instance stored according to international regulations) SNF, radioactive wastes or even the reactor are unlikely, based on a range of evaluations and assessments, to produce significant levels of contamination in the environment with respect to consequences for human health. Another group of potential accidents are those involving situations relating to the operation of the reactor and where the radioactive inventory of the reactor can be dispersed to the wider environment. These risks have not been included in the previously discussed assessment.

In a situation where the reactor reaches a supercritical state a large amount of energy is created in an uncontrolled fashion. This energy can result in damage to the reactor, its fuel and associated equipment resulting in the potential for discharge of fuel and radioactive inventory as well as radioactive steam or vapours. Short lived fission products may be released if the time between fission and release is short. The probability of a criticality accident occurring during day to operations of the reactor is small as control systems are in operation and safety systems can prevent the criticality occurring. Probability is however significantly higher however during activities such as those involved in refuelling operations.

A second type of accident involving the reactor is a loss of cooling accident, which unlike criticality accidents, usually occur when the reactor is running during normal operation. Due to leakages in the primary cooling circuit or failures in the main coolant pumps (or such failures in the secondary coolant system) situations may arise of consequence to the reactor. In the first the coolant level in the reactor sinks and heat begins to rise in the reactor that can ultimately cause the reactor fuel to melt with the potential for release of inventory to the primary circuit or into the reactor containment. Although the reactor will normally shut down in such situations, the heat of the reactor (produced by radioactive decay) constitutes a problem and if not dissipated can result in overheating of the reactor fuel itself. Modern reactors are usually fitted with systems to ensure that the reactor is cooled at all times to avoid the consequences of fuel overheating. Once the reactor fuel is damaged, radioactivity in the form of gas and suspensions of dust can be released into the reactor compartment although the extent of the severity of this event is largely determined by the design of the reactor and the type of containment system surrounding it. Modern reactor designs, such as the KLT-40S feature a range of containments and safety features as discussed in section 2.4 to prevent pressure build-ups and dispersion of radioactivity outside of the containment system. Loss of coolant incidents therefore should, in light of information available as to the design of the KLT-40S and other potential FNPP reactor systems, present little chance of significant dispersal of radioactivity outside of the containment vessel.

That criticality accidents can occur with significant consequences is evidenced by three incidents involving this type of event on Russian submarines. The first of these happened in February of 1965 and was precipitated by the incorrect placement of the reactor cover after refuelling. To reset the cover, it had to be raised up with the control rods attached to it. The precautions taken to ensure that the control rods would not be raised

too far failed and the rods cleared the reactor to such an extent that the reactor attained a critical state. Some days later the procedure was repeated and criticality was attained for a second time, in this instance resulting in the generation of steam causing the lid to fall in an incorrect position and a fire started. The reactor was quenched using water but crew members sustained radiation injuries and the reactor itself was destroyed. In 1968 repair and maintenance operations on a submarine in Northwest Russia resulted in a malfunction in the reactors control rods resulting in their removal and criticality occurred. No contamination or injuries occurred. In 1985 a criticality incident occurred in the far North of Russia with a submarine that resulted in significant contamination and injury. After refuelling a submarine reactor, an incident occurred that resulted in removal of the control rods from the reactor which promptly went critical and resulted in 10 deaths and the contamination of some square kilometres with fuel and fission products.

Of all the accident types that can occur with the type of reactors to be used in FNPP's it is accidents during refuelling that probably present the greatest risk due to the risk of human error or other events and the fact that the reactor is to a certain extent exposed to the environment due to necessary opening of the containment vessel. Irrespective of all other factors, the probability of an accident occurring with any single operation or process increases with the frequency the operation is carried out. In that regard the probability of a criticality type accident occurring increases as the number of FNPP's increases and subsequently as the number of refuelling operations increase. Such increases however should be viewed with respect to the overall probability which remains low. Little information is available as to the safety systems or refuelling mechanisms to be present on FNPP's. However some material does indicate that situations such as those referred to above, in which control rods leaving the

reactor causing criticality, have been addressed.

4.6 Relevance to FNPP's in the Northern Regions

The extent to which previous analyses can be deemed relevant to the case of FNPP's in the environment of the northern regions depends on a number of factors. Probabilities of various events such as collision, grounding, damage from ice floes etc were determined for those assessments based on international statistics. It is possible that the probability of various events occurring as a result of conditions in the northern regions are greater or less than the average global value. Irrespective of that it is unlikely that the severity of an event would be any greater or less because of its happening in the environment of the far north. It cannot be denied however that the chances of an accident involving transportation of nuclear materials increases with the total number of vessels in an area or the total number of transportations and in that regard the presence and transport of such vessels in and out of the northern regions increases the chances of an accident occurring although the overall probability is low.

The sensitivity of the northern regions to both radioactive contamination or even the possibility of radioactive contamination is problematic given the rich natural marine resources of the region and its socio-economic importance to a number of countries. How the presence of facilities such as FNPP's could potentially impact public perception of the contamination status of marine food products for example is rather difficult to determine but can probably be mitigated to some extent through effective monitoring regimes. For the communities served by such facilities, the benefits are likely to outweigh any perceived disadvantages. Public sensitivity therefore, as in the situation regarding contamination arising from European reprocessing facilities, is likely to be greatest among populations not directly benefiting from such facilities.

Evidence of the previous 5 decades indicate that much of the actual (and a significant proportion) of the perceived health and environmental risk associated with the operations of civilian (or military) fleets arises from their support infrastructures ashore rather than the vessels themselves. The problems associated with nuclear legacy facilities in the northern areas is well known, long standing and has proved difficult to resolve. The extent to which the underlying causes as opposed to the symptoms of such problems have diminished in modern times is difficult to determine although it is probable that restructuring of the Russian nuclear industry and improvements in its record over the years since Chernobyl plus the fact that many of the problems in the support structures of the Russian nuclear fleets arose before the development of international agreements mean that such situations are unlikely to arise again. What does constitute a significant concern however is the potential situation whereby a revitalised nuclear industry establishes itself in the Russian north and comes to rely upon or place even more pressure upon the extant infrastructure which has already proved itself somewhat deficient in many ways. This situation could arise where a rapid growth of FNPP and related business occurs and with which the development of the land based support infrastructure of waste handling facilities, refuelling sites, ship yards etc. (which naturally takes more time to develop than the capacity for reactor production) cannot or do not keep pace. The industry and the time scales involved however mean that there is a lag period between the production of FNPP facilities and the point at which pressure is most likely to be exerted on shore based support infrastructure as according to the information available, the first cycle of defueling, waste handling, decommissioning etc. will not occur until a decade after the production starts.

What should not be underestimated either in this regard is the pressure of the international market. This is an influence that here to fore

has not been a factor in the Russian nuclear maritime industry and may play a role in ensuring that situations such as those that arose in the 1960's through to the 1980's and the effects of which persist to this day will not arise. The requirements of producing a product for the international market are significantly different than those for producing for a domestic or military supply. All indications are that Russia will be producing a product in the face of competition from other producers such as Japan, France and Canada, all of whom are pursuing the same line of technology development for the same potential customers which may also serve to exert an influence serving to prevent the reoccurrence of past problems or the exacerbation of existing legacy ones.

4.7 Main points

- There is a considerable lack of clarity as to how existing international regulations and frameworks apply to the business models developed which will facilitate FNPP's and associate technologies as commercial products.
- Despite a lack of risk and environmental assessments it is possible to extrapolate existing assessments to FNPP's and such extrapolation indicates that there is little extra risk intrinsic to FNPP technology over and above that posed by land based facilities.
- International assessments indicate that where international regulations and recommendations are adhered to, transport of SNF, nuclear fuel and radioactive wastes poses little risk to either environment or human health.
- The risk of widespread environmental or human health impacts from FNPP's would not seem to be much greater than that which exists for civilian nuclear vessels. Based on analysis of previous accidents involving nuclear powered vessels, the risk of widespread significant environmental

contamination or human health impacts from FNPP's appears low.

- Irrespective of this, the risk of an accident, however small, is increased by the presence and transport of FNPP's and particularly with respect to increases in the number of operations such as refuelling which have caused accidents before.
- While risk of actual environmental or health impacts is low, previous experience has shown that public sensitivity to such facilities is extremely high and impacts from an accident, however minor, can be significant on, for example, public confidence in food products from the area.
- Aside from any problems or risks associated with FNPP's themselves, there is potential for environmental and other risks due to the operation of shore based facilities for the purpose of refuelling, waste handling, decommissioning and other activities.

5 Security and Non-proliferation

Although environmental and human health concerns have been the primary focus with respect to nuclear issues for many years, the situation after the events of September 2001 has pushed two other issues to the fore in relation to nuclear power and the industry. These two factors are non-proliferation and security and the development of an FNPP industry has served to amplify these concerns to some extent.

5.1 Non-proliferation

Non-proliferation has faced new challenges with the resurgence of the nuclear industry in an environment that little resembles that at the time of the first explosion of nuclear growth. The early decades of the nuclear age operated

under the assumption that only state entities or states would seek to or could effect the diversion of nuclear materials from peaceful civilian use to military use. The later decades saw that assumption change and it is now widely accepted that individuals or groups of individuals may seek to appropriate nuclear materials for a variety of malicious uses. This new reality has two aspects of interest regarding the new FNPP industry. The first of these is what materials and in what amounts the industry will potentially make available and the second is how will it secure those materials or prevent their being used or obtained for use for malicious purposes.

Small nuclear power plants including those indicated as potential units in FNPP's can be designed with intrinsic anti-proliferation design features such as high fuel burn-up rates, a fuel matrix that complicates reprocessing and a low ratio of fissile material to fuel matrix. Cheun and Reistad (58) provide a useful overview of aspects related to security, non-proliferation concerns and FNPP's and an overview of new business models in the nuclear industry in the context of risks to non-proliferation has been provided by Braun (58). Nuclear power plants in themselves do not pose a significant non-proliferation risk. No incident has ever occurred where significant amounts of fissile material were diverted from a functioning nuclear power plant.

Some of the FNPP designs that are potentially going to see realisation in the coming few years can be seen (and are stated) to have inbuilt anti-proliferation measures. The KLT-20 and ABV designs which do not feature on-site fuelling at all, complicate the potential for unauthorised access to fuel. Proliferation concerns have so far primarily centred on the enrichment level of the fuel used in the FNPP's. Fuel enriched to a level higher than 20% is more attractive with respect to its being used for a fission type weapon. There are no credible indications over the last four years that highly enriched fuel is intended for use in

FNPP's for either use in Russian territory or for export. There are indications from the literature as discussed previously that Russia has both developed and tested low enriched fuel for use in reactors such as the KLT-40S. FNPP's using fuel enriched to a level of 20% constitute no more of a target for the theft of fuel for use in nuclear weapons than any land based facility. However the fact that the use and production of FNPP's is dependant on their being economically viable and that that viability could theoretically be improved by the utilisation of more enriched fuel is a matter of some concern. And yet modifications such as that of the KLT-20 seem to indicate that a solution to limited reactor lifespan is being sought by designing systems requiring less refuelling than by increasing enrichment levels. Fuel design for all the reactor designs incorporates physical features designed to make the fuel less attractive for proliferation purposes. Again it must be emphasised that Russia's main focus appears to be towards development of a commercial product, the realisation of which would undoubtedly be complicated by the use of highly enriched fuel and would not contribute towards the viability of the product. The commercial model described by Russia and detailed in reports to IAEA CRP's and in the literature evidence that exists describes a system whereby Russia leases use of the plants to countries whilst never transferring ownership and provides both personnel and facilities for refuelling and receipt of SNF and waste is viewed as a non-proliferation measure by the IAEA..

5.2 Security

The security of FNPP's and associated nuclear materials can be viewed as having two facets: the security of the stationary plant itself and its nuclear materials during operation and the security of the plant and its materials when under transport during which time it can be considered to be a transport of nuclear or spent nuclear fuel and waste.

Although Russia contends that FNPP's will be subject to the same level of security as land based plants, it can be argued out that FNPP's can be more vulnerable to nuclear terrorism or blackmail and that security measures taken for land based plants cannot reasonably be applied to FNPP's (ie. walls cannot be built and exclusion zones will be open sea nor can vulnerable structures be located underground). It is worth noting that security measures on Russia's icebreaker fleet have been substantially improved as part of programmes conducted with international assistance and it is probable that such measures applied and experience gained will facilitate transfer of such systems to FNPP's. Transport of the FNPP's is a matter if some security concerns as journeys can be long and in many cases it is likely that the return journey will be made with significant amounts of wastes and SNF on board. How the presence of presumably Russian security personnel and their ability to protect an FNPP outside of Russian territory is a matter of potential confusion with respect to international legal systems. For discussion of safety, see the previous and relevant earlier sections.

5.2.1 Security of FNPP related land based facilities

In discussing potential security for the land based aspects of any FNPP industry it is useful to examine the security around the only current civilian analogue, Atomflot and the civilian nuclear icebreaker fleet. Fresh nuclear fuel for icebreakers arrives at Atomflot by rail and the fuel is then moved immediately to the service ship *Imandra*. The fuel is located in two storage units within the hull of the ship, while SNF is stored in a separate designated area on board the same ship. Atomflot has imposed a 2 km security zone around the entire facility and patrol vessels of the Russian Navy guard the northern and western seaward approaches. A double security fence with intrusion monitoring/detection systems and manned guard towers secures the eastern perimeter of the facility which is also equipped with

security fencing and intrusion monitoring/detection systems. Russian guard personnel from the Interior Ministry patrol all land perimeters and the only pedestrian access point which is within the administration facility itself is also manned. Collaborative efforts between the US and Russia on upgrading security at Atomflot began in 1996 and expanded to include Norway and Sweden. The vulnerability of the facility was evaluated in a joint effort by these four countries in 1996 and the results of that analysis were used to enhance security further at the facility. These efforts have focussed on securing both fresh fuel at the site and the security of service vessels and nuclear materials from malicious activity. Security systems at the site are advanced and on a par with security systems at other sensitive locations worldwide. Overviews of collaborative security efforts at the Atomflot facility can be found in Shuvlova (60). The security of any land based FNPP facilities is no different to the security of any nuclear facility and it seems illogical to conclude that FNPP facilities pose any special security risk.

5.2.2 Transport security

Between 1971 and 2003 some 20'000 shipments of SNF and high radioactive wastes have been undertaken, a proportion of these by sea (61) and primarily on routes between the Far East and the nuclear industrial centres of Great Britain and France. There have been more than 160 shipments of used nuclear fuel from Japan to Europe and fresh reactor fuel (MOX) has been shipped from Europe to Japan between 1999 and 2001. 12 shipments of vitrified nuclear waste from Europe to Japan have taken place between 1999 and 2007. Lesser numbers of shipments of plutonium have taken place. Shipments of nuclear materials between the Far East and Europe are conducted using 100 t Type B containers as described earlier. The vessels used for the transports are 104 m, 5100 t vessels specially designed and double-hulled vessels belonging to the British-based company Pacific Nuclear

Transport Ltd (PNTL) and conform to all relevant international safety standards being classed as INF-3 vessels.

This realisation has been reflected by the IAEA in its publication INFCIRC/225/Rev.4 “*The Physical Protection of the Nuclear Material and Nuclear Facilities*” (51) which serves as recommendations for guiding member states in the security of nuclear facilities and materials including those under transport. Although the security of such materials is the responsibility of the state using them, the interest of other states in the fulfilment of those responsibilities is noted in INFCIRC/225. The IAEA considers nuclear materials to be at most risk during transport and that risk minimisation should be achieved by reducing the amount of time during which nuclear materials are under transport, minimising the total number of transfers, protection of the material under transport in an appropriate manner for the material involved, avoiding the use of regular routes or schedules and limiting the number of persons with advance knowledge of the transportation. This vulnerability initiated the IAEA to draft “*The Convention on the Physical Protection of Nuclear Material*” (CPPNM) which entered into force in 1987 and to which Russia is a member. Under the CPPNM a number of security precautions are required for various defined classes of nuclear material during international transport. As such it may be that the CPPNM only applies to FNPP’s leaving or entering the Russian territory and not to FNPP’s remaining within Russian territory.

These classes of material in so far as they are relevant to FNPP’s are I and II. The levels of protection required for these categories of material under the CPPNM are as follows:

- Levels of physical protection for nuclear material during storage incidental to international nuclear transport include:

1. For Category III materials, storage within an area to which access is controlled;
 2. For Category II materials, storage within an area under constant surveillance by guards or electronic devices, surrounded by a physical barrier with a limited number of points of entry under appropriate control or any area with an equivalent level of physical protection;
 3. For Category I material, storage within a protected area as defined for Category II above, to which, in addition, access is restricted to persons whose trustworthiness has been determined, and which is under surveillance by guards who are in close communication with appropriate response forces. Specific measures taken in this context should have as their object the detection and prevention of any assault, unauthorized access or unauthorized removal of material.
- Levels of physical protection for nuclear material during international transport include:
 1. For Category II and III materials, transportation shall take place under special precautions including prior arrangements among sender, receiver, and carrier, and prior agreement between natural or legal persons subject to the jurisdiction and regulation of exporting and importing States, specifying time, place and procedures for transferring transport responsibility;
 2. For Category I materials, transportation shall take place under special precautions

identified above for transportation of Category II and III materials, and in addition, under constant surveillance by escorts and under conditions which assure close communication with appropriate response forces;

3. For natural uranium other than in the form of ore or ore-residue; transportation protection for quantities exceeding 500 kilograms uranium shall include advance notification of shipment specifying mode of transport, expected time of arrival and confirmation of receipt of shipment.

The IAEA and IMO have envisaged two main ways in which nuclear/radiological terrorism may take place with respect to transportation of nuclear materials:

- Attack or sabotage on the cargo or vessel carrying nuclear materials,
- Diversion or theft of nuclear materials for the manufacture of a nuclear weapon.

A range of scenarios have been suggested by a range of bodies relating to how either of the above could be achieved in relation to transported nuclear materials usually relating to technical details of how terrorists could gain access to nuclear materials being transported within the types of containers usually employed for transportation. The actions of environmental activist parties in the past has demonstrated that groups of people can approach, interfere with and in some cases board vessels containing nuclear materials.

Regarding security of FNPP's and transports of nuclear materials by sea as a result of the operation of FNPP's, two aspects are of concern. The first of these is the extent to

which current national and international regulations under which the operation of FNPP's may be expected to fall adequately address the security of such facilities and materials in the current security environment. Bodies such as the IAEA and IMO have in the years after 2001 conducted a number of activities aimed at addressing possible weaknesses in current regulations with respect to terrorist activities and the security of nuclear materials. The CPPNM is a legally binding treaty but is presented in general enough terms that a certain flexibility is built in. It should also be noted that states who have assigned up to the CPPNM are only obliged to adhere to it is so far as they consent to such an obligation. A useful discussion of the vulnerabilities of international agreements and regulations with respect to seagoing transportation of nuclear and radioactive materials is that provided by Suzette and Suarez (2003) and ⁶³Van Dyke (2003). The IAEA's INFCIRC 225 system is more detailed than the CPPNM and the mandatory details of the system (such as vessel design etc.) do constitute a layer of security on the transport of nuclear materials.

The second is the extent to which FNPP's and their operations, both within Russian territory and as export products (in the classical sense or as products under the type of commercial models as have been introduced earlier) fall under such systems as CPPNM. FNPP's may occupy a grey area with respect to whether or not they are transport vessels or stationary facilities. The legal status of FNPP's under such systems as "*Build-Own-Operate*" is also relatively unclear with respect to regulation. In a similar manner, the situation regarding Russian security personnel or Russian plant personnel acting in relation to security on an FNPP going through or stationed in the territory of another country would seem to present possible legal complications.

6 Summary

Although floating nuclear power plants are not a new concept, all indications are that Russia, amongst other countries, has identified FNPP's (floating nuclear power plants) as one of a range of potential power solutions for both the domestic and international commercial market, utilising LCNPP's (low-capacity nuclear power plants). This focus on LCNPP's in general and LCNPP's in particular appears to be a key part of Russia's positioning of itself as a future leader in the global nuclear energy market. Given the fact that much of the support infrastructure for Russia's existing civilian nuclear fleet is located in the northern regions, the development of FNPP's as part of the nuclear industry is a matter of some interest to a number of countries including Norway. Although FNPP technology is not new, the business models being proposed to effectively commercialise FNPP's as a product on the international market are somewhat novel. This novelty may place FNPP's in a relatively grey area with respect to international laws and regulations. This situation is however also a product of recent developments and initiatives regarding the global nuclear industry and how it operates in the 21st century and the consideration of such business models by countries other than Russia means that it may not be unique to either FNPP's or Russia.

A review of the available information indicates that FNPP's may be constructed, located and operated in the Russian Arctic region for a variety of purposes (civilian power/heat generation, resource extraction etc.) as well as being made available for export internationally for purposes such as desalination. Russia is and has been engaged in marketing of such systems to a wide range of potential customers. Information as to potential FNPP technologies is available from a range of sources which indicate a suite of potential designs that may be used in FNPP systems. The nature of these plants, with respect to operation, life cycle, waste handling etc. varies considerably. The

design currently of most relevance, that of the KLT-40S based *Academician Lomonosov*, is a non-propelled barge like vessel featuring facilities for onboard waste storage, fresh fuel and SNF storage.

Areas of concern regarding the development, use and export of FNPP technologies as well as the advent of a nuclear industry based upon them are numerous. The presence of new nuclear power generation facilities in the northern regions will affect the risk of accidents and incidents that may impact upon human health, environmental quality and the socio-economic aspects of the region that have proved and continue to be vulnerable to actual and potential radioactive contamination. The transport of nuclear materials in and out of the region as part of an export based FNPP industry as well as the situation regarding land based industrial nuclear facilities required to support such an industry and the associated risks are also a matter of obvious concern.

References

[1] Alekseev PN et al. Functions of low-capacity nuclear power plants in supplying energy. *Atomic Energy* 2007; 102(4): 203-208.

[2] Bratton J. The United States army nuclear power programme: its reactors and their applications to less developed areas throughout the world. In: *International conference on small and medium power reactors*. Vol. 1. Vienna: International Atomic Energy Agency, IAEA, 1961: 255-268.

[3] Sidorenko, V. The history of atomic energy of the Soviet Union and Russia. Vol. 5. Moscow: IzdAT, 2004.

[4] Alekseev AI et al. ATU-2 enhanced safety reactor facility for supplying electricity and heat. *Energeticheskoe stroitel'stvo* 1994; 4: 17-23. (In Russian)

[5] Kostin VI et al. 2007. VBER-300 reactor system and power-generating units for regional nuclear power production. *Atomic Energy* 2007; 102(1): 36-41.

[6] Baranaev YuD, Orekhiv YuI, Sergeev A. Emergency heat removal in the integral water cooled ABV-6 reactor for the Volnolom floating nuclear power plant. In: *Integral design concepts of advanced water cooled reactors*. IAEA-TECDOC-977. Vienna: International Atomic Energy Agency, IAEA, 1997: 161-171. http://www-pub.iaea.org/MTCD/publications/PDF/te_977_prn.pdf (2009.01.06)

[7] Vasyukov VI et al. Russian concepts of nuclear power plants with small reactors

without on-site refuelling. In: *Innovative small and medium sized reactors: Design features, safety approaches and R&D trends*. IAEA-TECDOC-1451. Vienna: International Atomic Energy Agency, IAEA, 2004: 103-124. http://www-pub.iaea.org/MTCD/publications/PDF/TE_145_1_web.pdf (2009.01.06)

[8] Alekseev PN, Udyanskii YuN, Shchepetina TD. MARS fuel microelement reactor with liquid salt coolant. *Atomnaya Energiya* 2002; 93: 3-13 (In Russian).

[9] Sidorenko VA. Research and development work on nuclear reactors for power production in Russia. *Atomic Energy* 1997; 90(6): 433-441.

[10] Lewis C. Floating N-plants: Breaking new ground in Russia's frozen north. *Nucnet* no. 294/96, 11 June 1996. Brussels: Nucnet News Agency, 1996.

[11] Panov YuK, Sandler NG. Nuclear vessel Ural: a floating electric power plant, (FBIS-UST-97-016). *Atomnaya Energiya* 1997: 149-151.

[12] Ustinov Y. Nuclear power engineering on Kamchatka: Bluff or reality?. *Krasnaya zvezda*, 12 May 1999. In: *Nuclear subs to power Kamchatka in crisis*, FBIS Document FTS19990513000109, 12 May 1999. Reston, Va: Foreign Broadcast Information Service, 1999.

[13] Rybalchenko I. Friendship of the peoples: peaceful atom to float with China's assistance. *Kommersant*, 24 July 2003. In: *Russia, China sign protocol on floating nuclear power station project*. FBIS Document CEP20030724000174. Reston, Va: Foreign Broadcast Information Service, 2003.

[14] AFP (Agence France Presse). Russia proposes floating nuclear power plant to Indonesia. FBIS Document UPP20030420000056. Reston, Va: Foreign Broadcast Information Service, 2003

[15] U.S. Army Corps of Engineers. Methods and sources of disposal of the nuclear barge "Sturgis". February 2000.

[16] U.S. Army Corps of Engineers. Sampling and analysis plan: Decommissioning of the nuclear barge "Sturgis", James River Reserve Fleet, Ft. Eustis, Virginia. July 2001.

[17] Golovin A et al. Utilisation of floating nuclear power plants in northern regions. *Atomnaya Energiya* 1981; 51(2): 83-87. (In Russian).

[18] United Nations Educational Scientific and Cultural Organisation (UNESCO). Water for people, water for life. UN World Water Development Report (WWDR). Paris: UNESCO, 2002.
http://portal.unesco.org/en/ev.php-URL_ID=29560&URL_DO=DO_TOPIC&URL_SECTION=201.html (2009.01.06)

[19] Economics of nuclear desalination: New developments and site specific studies. Final Report of a Coordinated Research Project 2002-2006. IAEA-TECDOC-1561. Vienna: International Atomic Energy Agency, IAEA, 2007.
http://www-pub.iaea.org/MTCD/publications/PDF/te_1561_web.pdf (2009.01.06)

[20] Polunichev VI, Fateev SA, Gureeva LV. Economic evaluation of nuclear power and desalination complexes. In: Economics of nuclear desalination: New developments and site specific studies. Final Report of a

Coordinated Research Project 2002-2006. IAEA-TECDOC-1561. Vienna: International Atomic Energy Agency, IAEA, 2007: 173-187.
http://www-pub.iaea.org/MTCD/publications/PDF/te_1561_web.pdf (2009.01.06)

[21] Kostin VI et al. Floating power-generating unit with a KLT-40S reactor system for desalinating sea water. *Atomnaya Energiya* 2007; 102(1): 31-35 (In Russian).

[22] Konishi T, Faibish RS, Gasparini M. Application of nuclear energy for seawater desalination: Design concepts of nuclear desalination plants. In: Proceedings of the 10th international conference on nuclear engineering (ICONE 10), Arlington Virginia 2002. New York: American Society of Mechanical Engineers, ASME, 2002.

[23] Status of design concepts of nuclear desalination plants, IAEA-TECDOC-1326. Vienna: International Atomic Energy Agency, IAEA, 2002.
http://www-pub.iaea.org/MTCD/publications/PDF/te_1326_web.pdf (2009.01.06)

[24] Barents Observer. Murmansk gets the world's first nuclear-powered oil drilling vessel. 2007-08-07.
<http://www.barentsobserver.com/index.php?id=526765> (2009.01.06)

[25] Ria Novosti. Russia says no plans to store foreign spent nuclear fuel. RIA Novosti, 11-07-2006. Moskva 2006.
<http://en.rian.ru/russia/20060711/51174005.html> (2009.01.06)

[26] Polushkin AK et al. Implementation of the project for the construction and operation of a nuclear heat and power plant on the basis of a floating power unit with KLT-40C reactors. In:

Small power and heat generation systems on the basis of propulsion and innovative reactor technologies IAEA-TECDOC-1172 Vienna: International Atomic Energy Agency, IAEA, 2000: 53-65. http://www-pub.iaea.org/MTCD/publications/PDF/te_1172_prn.pdf (2009.01.06)

[27] Mitenkov FM, Averbakh BA, Antyufeeva IN. Economic effect of the development and operation of serially produced propulsion nuclear power systems. Atomic Energy 2007; 102(1): 42 – 47.

[28] ROSATOM. Interview with deputy director general of Rosenergoatom concern Sergey Krysov. 2007. Moscow: Press Center of Nuclear Energy and Industry, 2007. http://www.rosatom.ru/en/news/7108_19.11.2007 (2009.01.06)

[29] ROSATOM. Atomflot to be given to Rosatom. Moscow: Press Center of Nuclear Energy and Industry, 2008. http://www.rosatom.ru/en/news/8452_15.02.2008. (2009.01.06)

[30] Arctic Monitoring and Assessment Programme (AMAP). Arctic pollution issues: Radioactive contamination. Østerås: Norwegian Radiation Protection Authority, 1997.

[31] Kostin VI et al. VBER-300 reactor system and power-generating units for regional nuclear power production. Atomic Energy 2007; 102(1): 36 – 41.

[32] KLT-40 floating nuclear heat and power unit with KLT-40s reactor plant (OKBM, Russian Federation). In: Status of advanced light water reactor designs IAEA-TECDOC-1391. Vienna: International Atomic Energy Agency, IAEA, 2004: 733-754. http://www-pub.iaea.org/MTCD/publications/PDF/te_1391_web.pdf (2009.01.06)

http://www-pub.iaea.org/MTCD/publications/PDF/te_1391_web.pdf (2009.01.06)

[33] Status of small reactor designs without on-site refuelling. IAEA-TECDOC-1536. Vienna: International Atomic Energy Agency, IAEA, 2007. http://www-pub.iaea.org/MTCD/publications/PDF/te_1536_web.pdf (2009.01.06)

[34] Reistad O, Ølgaard PL. Russian nuclear power plants for marine applications. Report NKS-138. Roskilde: Nordic Nuclear Safety Research, NKS, 2006. <http://www.nks.org/dk/publikationer/soegefunktion/?tx=nks-138> (2009.01.06)

[35] Beliaev V, Polunichev V. Basic safety principles of KLT-40C reactor plants. In: Small power and heat generation systems on the basis of propulsion and innovative reactor technologies IAEA-TECDOC-1172 Vienna: International Atomic Energy Agency, IAEA, 2000: 29-41. http://www-pub.iaea.org/MTCD/publications/PDF/te_1172_prn.pdf (2009.01.06)

[36] Kostin VI et al. Small floating nuclear power plants with ABV reactors for electric power generation, heat production and sea water desalination. In: Proceedings of the Fifteenth Annual Conference of the Indian Nuclear Society, INSAC 2004: Nuclear technology and social needs, 15th-17th November 2004, Mumbai, India. Mumbai: Indian Nuclear Society, 2004.

[37] Baranev YuD, Orekhiv YuI, Sergeev A. Emergency heat removal in the integral water cooled ABV-6 reactor for the Volnolom floating nuclear power plant. In: Integral design concepts of advanced water cooled reactors IAEA-TECDOC-977. Vienna: International Atomic Energy Agency, IAEA, 1997: 161-171. http://www-pub.iaea.org/MTCD/publications/PDF/te_977_web.pdf (2009.01.06)

pub.iaea.org/MTCD/publications/PDF/te_977_prn.pdf (2009.01.06)

[38] Glaser A, von Hippel F. On the importance of ending the use of HEU in the nuclear fuel cycle: an updated assessment. In: International Meeting on Reduced Enrichment for Research and Test Reactors, RERTR, San Carlos de bariloche, Argentina, November 3-8, 2002. Argonne, Il: Argonne National Laboratory, 2002. http://www.princeton.edu/~aglaser/2002aglaser_bariloche.pdf (2009.01.06)

[39] Diakov AC et al. Feasibility of converting Russian icebreaker reactors from HEU to LEU fuel. Science and Global Security 2006; 14: 33-48. <http://www.armscontrol.ru/pubs/en/heu-leu-reactors-sgs.pdf> (2009.01.06)

[40] Nilsen T, Bøhmer N. Sources of radioactive contamination in Murmansk and Arkhangel'sk counties. Bellona report no.1, 1994. Oslo: Bellona Foundation, 1994.

[41] Belyayev V, Leontyev K. Reactor out to sea.. Nuclear Engineering International 2004; 49(594): 18-20.

[42] Savchenko A et al. Dispersion type zirconium matrix fuels fabricated by capillary impregnation method. Journal of Nuclear Materials 2007; 362: 356-363.

[43] ITAR-TASS news agency. Russia to start building floating nuclear power plant in 2006, January 12, 2006. http://www.redorbit.com/news/science/355871/russia_to_start_building_floating_nuclear_power_plant_in_2006/ (2009.01.06)

[44] Vatulin AV et al. Development of core fuel elements for floating power units (FPU) and nuclear low-power plants (NLPP): status

and prospects. In: Proceedings of the 7th Russian Conference on Reactor Materials Science, Dimitrovgrad, Russia, 2003.

[45] Innovative small and medium sized reactors: Design features, safety approaches and R&D trends. IAEA-TECDOC-1451. Vienna: International Atomic Energy Agency, IAEA, 2005. http://www-pub.iaea.org/MTCD/publications/PDF/TE_1451_web.pdf (2009.01.06)

[46] Small power and heat generation systems on the basis of propulsion and innovative reactor technologies: Proceedings of an Advisory Group meeting held in Obninsk, Russian Federation, 20-24 July 1998. IAEA-TECDOC-1172. Vienna: International Atomic Energy Agency, IAEA, 2000. http://www-pub.iaea.org/MTCD/publications/PDF/te_1172_prn.pdf (2009.01.06)

[47] Shadrin AP, Kuz'min AN. Radioactive waste utilisation and decommissioning of low-power nuclear power stations under Arctic conditions. Atomnaya Energiya 1997; 83(2): 100-102.

[48] Reistad O, Ølgaard PL. Inventory and source term evaluation of Russian nuclear power plants for marine applications. NKS-139. Roskilde: Nordic Nuclear Safety Research, 2006. <http://www.nks.org/dk/publikationer/soegefunktion/?tx=nks-139> (2009.01.06)

[49] Humphries JR, Davies K. A floating desalination/co-generation system using the KLT-40 reactor and Canadian RO desalination technology. In: Small power and heat generation systems on the basis of propulsion and innovative reactor technologies. IAEA-TECDOC-1172. Vienna: International Atomic Energy Agency, IAEA, 2000: 41-53. <http://www->

pub.iaea.org/MTCD/publications/PDF/te_1172_prn.pdf (2009.01.06)

[50] von Welck S. Third United Nations conference on the law of the sea and the use of nuclear energy. Nuclear Law Bulletin 1975 (15): 62-72.
<http://www.nea.fr/html/law/nlb/NLB-15-EN.pdf> (2009.01.06)

[51] The physical protection of nuclear material and nuclear facilities. INFCIRC/225/Rev.4 (Corrected). Vienna: International Atomic Energy Agency, IAEA, 1998.
http://www.iaea.org/Publications/Documents/Infircs/1999/infirc225r4c/rev4_content.html (2009.01.06)

[52] Beaufoy M. Is the law of the sea ready for nuclear leasing?. Macquarie Journal of International and Comparative Environmental Law 2006; 3(2): 91-117.
http://www.law.mq.edu.au/html/MqJICEL/vol3/2_05Beaufoy.pdf (2009.01.06)

[53] OTA (Office of Technology Assessment). Coastal effects of offshore energy Systems: Oil and gas, deepwater ports and offshore nuclear powerplants off the coast of New Jersey and Delaware. Volume 1: Working paper 1 thru 3. NTIS #PB-274033, OTA-O-37. Washington DC: OTA, 1976.

[54] Iosjpe M, Reistad O, Amundsen I. Radioecological consequences of a potential accident during transport of radioactive materials along the Norwegian coastline StrålevernRapport 2007:3. Østerås: Norwegian Radiation Protection Authority, 2007.
http://www.nrpa.no/archive/Internett/Publikasjoner/Stralevernrapport/2007/StralevernRapport_3_2007.pdf (2009.01.06)

[55] Amundsen I, Lind B, Reistad O, Gussgaard K, Iosjpe M, Sickel, M. The Kursk accident. StrålevernRapport 2001:5. Østerås: Norwegian Radiation Protection Authority, 2001.
http://www.nrpa.no/archive/Internett/Publikasjoner/Stralevernrapport/2001/StralevernRapport_5_2001.pdf (2009.01.06)

[56] Predicted radionuclide release from marine reactors dumped in the Kara Sea: Report of the Source Term Working Group of the International Arctic Seas Assessment Project (IASAP). IAEA-TECDOC-938, Vienna: International Atomic Energy Agency, IAEA, 1997.
http://www-pub.iaea.org/MTCD/publications/PDF/te_0938_scr.pdf (2009.01.06)

[57] Severity, probability and risk of accidents during maritime transport of radioactive material: Final report of a co-ordinated research project 1995–1999. IAEA-TECDOC-1231. Vienna: International Atomic Energy Agency, IAEA, 2001.
http://www-pub.iaea.org/MTCD/publications/PDF/te_1231_prn.pdf (2009.01.06)

[58] Chuen CH, Reistad O. Sea fission: Russia's floating nuclear power plants. Jane's Intelligence Review 2007; 19(12): 48-52.

[59] Braun C. The nuclear energy market and the non-proliferation regime. Non-proliferation Review 2006; 13(3): 627 – 644.

[60] Shuvalova A. Cooperation between Russia and the United Kingdom under the global partnership. Yaderny Control 2004; (3): 125–144.

[61] World Nuclear Association. Japanese waste and MOX shipments from Europe. London: World Nuclear Association, 2007.

<http://www.world-nuclear.org/info/inf39.html>
(2009.01.06)

[62] Suzette A, Suarez V. Post September 11 security challenges to the legal regime of the maritime carriage of nuclear and radioactive materials. *The International Journal of Marine and Coastal Law* 2003; 18(3): 423-440.

[63] Van Dyke J. Perspective: Balancing navigational freedom with environmental and security concerns. *Colorado Journal of International Environmental Law and Policy* 2003, 15 (Yearbook).

List of Abbreviations

LCNPP – Low Capacity Nuclear Power Plant

LRW – Liquid radioactive waste

FNPP – Floating Nuclear Power Plant

GW(e) – Gigawatts of electrical energy

MED – Multi effect desalination

MW(e) – Megawatts of electrical energy

MW(t) – Megawatts of thermal energy

RO – Reverse osmosis

SNF – Spent nuclear fuel

SRW – Solid radioactive waste



StrålevernRapport 2008:1
Virksomhetsplan 2008

StrålevernRapport 2008:2

Совершенствование Российской нормативной базы в области обеспечения безопасности при выводе из эксплуатации и утилизации радиоизотопных термоэлектрических генераторов

StrålevernRapport 2008:3

Mayak Health Report. Dose assessments and health of riverside residents close to "Mayak" PA

StrålevernRapport 2008:4

Bruk av laser og sterke optiske kilder til medisinske og kosmetiske formål

StrålevernRapport 2008:5

Strålevernets overvåking av radioaktivitet i luft – beskrivelse og resultater for 2000–2004

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Strålevernet si overvåking av radioaktivitet i luft – resultatrapport for luftfilterstasjonar 2005–2006

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Regulatory improvements related to the radiation and environmental protection during remediation of the nuclear legacy sites in North West Russia. Final report of work completed by FMBA and NRPA in 2007

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Усовершенствование законодательного регулирования в области радиационной защиты и охраны окружающей среды при проведении реабилитационных работ в местах расположения объектов ядерного наследия на северо-западе России. Окончательный отчет по работам, выполненным ФМБА и НРПА в 2007 г

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Nordic society for radiation protection – NSF5

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