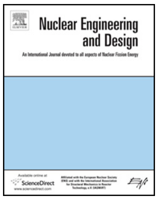
Nuclear Engineering and Design 293 (2015) 176–186

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes



Historic survey on nuclear merchant ships

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HIGHLIGHTS

- The nuclear merchants ships already built are described and studied.
- Their history and main architectural choices are presented, focusing nuclear domain.
- The typical problems in those projects are discussed.
- Some key factors for developing successful nuclear merchant ships are identified.

ARTICLE INFO

Article history:
Received 26 July 2014
Received in revised form 6 July 2015
Accepted 14 July 2015

ABSTRACT

This work provides a survey on past nuclear merchant ships experience. On light of new regulations on CO_2, SO_x and NO_x, the options for clean naval propulsion need to be studied. Despite many efforts, the only already sea proven emissions-free energy is nuclear power of pressurized water reactor type. Given the past experience on the field, this work provides some information on history, architectures and hints of reasons for the success or failures of each project. It is found that adequate requirements identification must be done keeping economics always in the center of design. Experience shows, except after major catastrophic accidents, public trust may be earned by open dialog and sound engineering practices.

Contents

1. Introduction

Shipping is major atmosphere pollution source, being, according to Gravina et al. (2012), worldly responsible in 2007 for 2.7% of CO_2, 4–9% of SO_x and 15% of NO_x emissions (Eyring et al., 2009). This drove changes in regulations restricting the types of fuel oil, which may lead to elevation of fuel costs, which in turn, along the depletion of fossil fuels, may have impacts on shipping rates, profitability and uncertainties of the shipping market.

Nowadays, shipping is responsible by 95% of global commerce (Royal Academy of Engineering, 2013) and plays a key role on economy and prosperity.

Nuclear energy is, in the opinion of many experts, including (Jenkins, 2011), the only proven emissions free energy prone to substitute fossil fuels. Despite nuclear energy risks, it may avoid a much more frequent accident that is oil spill at sea. The prices of nuclear fuel are stable and low, reducing operating costs and uncertainties.

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http://dx.doi.org/10.1016/j.nucengdes.2015.07.031

Currently there is an experience of about 700 nuclear naval reactors worldwide (Royal Academy of Engineering, 2013) for military use and about 200 nuclear naval reactors are still in operation (Gravina et al., 2012). This experience shows naval reactors have higher operational reliability when compared to diesel motors (Carlton et al., 2011). The nuclear power also allows better flexibility in ship design given the smaller volume. Nuclear vessels operation is more flexible due less frequent refueling.

The most successful design is the pressurized water reactors, which have proven to be simple, safe and compact, becoming the dominant solution. Those characteristics are interesting for merchant ships because allow more space for goods deadweight.

Nowadays nuclear power plants with pressurized water reactors reach safety levels far beyond the first generation and costs have being reduced if compared with designs of the nineties.

A great deal of these improvements was achieved by use of passive systems for safety and plant simplification. Once naval reactors are always at sea, further simplifications may be realized.

On the other hand, there are some drawbacks, like the high capital cost, proliferation issues, and rigorous nuclear standards – essentially objective oriented while merchant ships standards are prescriptive – and they are subjected to nuclear authorities' inspections. Therefore, deep knowledge on nuclear field is required and nuclear classified shore installations are required, enhancing the global costs for a small number of ships, along with the problem of ownership of nuclear waste. Furthermore, public opinion became afraid of nuclear energy after Chernobyl and Fukushima accidents and many countries decided to abandon nuclear energy and nuclear merchant ships, like NS Otto Hahn and NS Sevmorput, have found many restrictions for entering in ports.

Despite all drawbacks, for large merchant ships, a number of studies indicate that it is, in theory, economically feasible to employ nuclear energy for large ships. There are technical and organizational solutions to cope with the drawbacks, like the current trend of studies on small modular reactors (Magwood, 2001; Hirdaris et al., 2014a,b,c), modular ship architectures to avoid the problem of entering in a harbor where nuclear energy is banished (Gravina et al., 2012), ownership of naval reactor by a nuclear energy enterprise and leasing by the ship owner, along with control by state nuclear authority.

On the military field, US Navy concluded that nuclear energy should be considered for medium size combat ships because the life cycle costs are about the same as conventional ships and there are many advantages, like better mobility, operational presence, better acoustic and infrared discretion and independence of tankers, making the fleet more effective (O'rourke, 2010). Apart antinuclear sentiment, US navy nuclear powered warships are welcome in 150 ports in 50 countries worldwide (O'rourke, 2010).

Another aspect is the need to keep military production to avoid competence losses, being cheaper to keep at least a small production than redevelop lost competences (Rand, 2007). In this context, it could be interesting to build nuclear merchant ships in order to keep military naval reactors production, taking benefits of scale production. This way, it is possible to profit from military naval reactors credibility and improve any nation's naval industry competitiveness. The nuclear infrastructure for military naval reactors could be used for support and maintenance of merchant ships nuclear reactors, avoiding, in a first moment, huge investments on ports.

Before entering into more detailed ideas about the use of nuclear energy, it is fundamental to investigate past experiences and understand their successes, failures and difficulties. For this work, four ships meant for normal navigation were chosen (NS Savannah, NS Otto Hahn, NS Mutsu, NS Sevmorput), excluding the icebreakers because it is a specific application and their history may not be applicable to typical merchant ships.

Table 1
NS Savannah reactor coolant system data.

Parameter	Value
Primary pressure	12.07 MPa
Primary mean temperature	264 °C
Primary coolant flow	1.009 m^3/s
Thermal power	70 MW
Steam generator pipe diameter	19.05 mm
Steam flow	32.76 kg/s
Steam pressure at nominal power	3.172 MPa
Steam pressure at zero power	5.033 MPa
Primary piping diameter	318 mm
Hot leg sub cooling	37.8 °C
Purification system flow	1.26e−3 m^3/s
Purification resin life	50 Days

Table 2
NS Savannah reactor core data.

Parameter	Value
Core height	1.68 m
Core diameter	1.57 m
Fuel rods diameter	10 mm
Mean UO2 enrichment	4.4%
Fuel pellets diameter	9 mm
Cruciform control element width	200 mm
Cruciform control el. thickness	10 mm
Cruciform control element length	1.68 m

2. NS Savannah

The Nuclear Ship Savannah is a boldly styled passenger/cargo vessel powered by a nuclear reactor. It was commissioned in 1962. She had been built on demand of Eisenhower president in the Atoms for Peace program (Lange, 1990). The objective was to demonstrate good will and not to achieve economical profit. The Maritime Administration wanted a laboratory to study the design, operation and manning of a nuclear merchant ship without economic considerations.

The proposed objectives were achieved and the operation of a low enrichment uranium core in a naval reactor was successful. The propulsion system had faster time response than a conventional plant (twice or four times faster). She spent 90 million dollars and earned 12 million in 5 operation years (Lange, 1990). The ship was dropped in 1971 because of economic feasibility, components reliability and wages disputes between engineers and deck officers. The deck officers did not accept to receive smaller salaries than the more qualified nuclear engineers who operated the reactor.

This ship was considered important to nuclear energy public acceptance. The nuclear energy was reserved at that time to weapons and military vessels (Lange, 1990).

She was a 21,800 ton ship, with cargo capacity of 10,000 ton and 60 passengers. The shaft line power was 16 MW. The ship was luxuriously decorated by Jack Heaney, with a deck exclusive for passengers, and decorated with paintings and sculptures made by American artists. Table 1 presents some parameters of the NS Savannah reactor coolant system (Baltra Aedo, 1977).

Unlike other naval reactors used by US Navy, NS Savannah used commercial low enrichment uranium and the project was completely civil, executed by Westinghouse. Table 2 shows the main reactor core data (Lange, 1990).

The nuclear containment system was composed by a 10.67 m diameter cylinder with 15.24 m length. It had spherical ends (Lange,

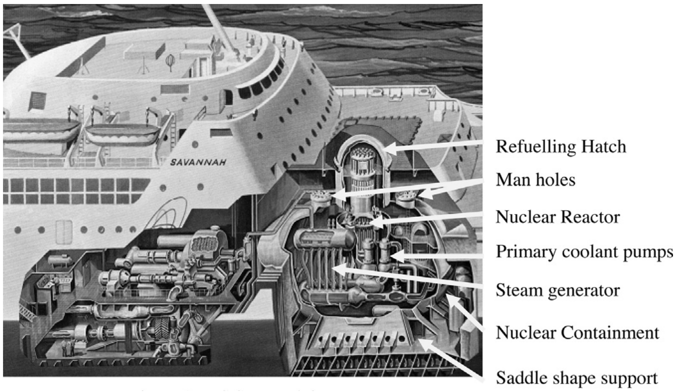


Fig. 1. NS Savannah layout.

1990). The containment was made of carbon steel of 10 cm thickness and it was designed to resist to 1.28 absolute MPa in case of loss of coolant accidents (Lange, 1990). Fig. 1 provides a general view of the arrangement in the ship (US Department of Transportation–Maritime Administration–Office of Ship Disposal, 2011).

It also had an opening with 4.3 m on top to make fuel recharges and four passageways for personnel access, being two at upper deck and two at lower deck. At 30.5 m depth, in case the ship sank, the lower deck passageways would rupture to avoid containment collapse. Half an hour after the shutdown, the radiation inside containment would drop below 2 Sieverts/h (Lange, 1990).

Fig. 2 shows the reactor core internals (US Department of Transportation–Maritime Administration–Office of Ship Disposal, 2011).

The nuclear containment lower half was supported by a steel structure. The secondary shield had a 1.22 m thick concrete wall in lower part. At the top nuclear containment half, there were lead (15.2 cm thick) and polyethylene (15.2 cm thick) layers. The primary shield, used to limit radiation inside nuclear containment, was a cylindrical tank around the reactor vessel with 4.7 m diameter and 5.5 m height. The primary shield had an 84 cm thick water annulus and a peripheral lead shielding varying in thickness from 2.54 cm to 10.16 cm of lead. The weight of the concrete shield is approximately 1187 tons and that of the lead and polyethylene is 616 tons. The containment vessel alone weighs 250 tons.

Additionally, both nuclear containment sides were protected by alternate wood and steel layers in total thickness of 61 cm in order to protect against collision. All those measures allowed considering the ship safe against collisions and bottoming. Fig. 3 provides a front cut view of the containment and layers of steel, concrete and wood (US Department of Transportation–Maritime Administration–Office of Ship Disposal, 2011).

There were resources to store radioactive waste onboard for at least 100 days. The training for the crew consisted of a 31 weeks theoretical course and 30 weeks field practice with 4 reactors startup and 4 reactors shutdown (Lange, 1990). Fig. 4 shows a top view of the general arrangement of main components inside nuclear containment (US Department of Transportation–Maritime Administration–Office of Ship Disposal, 2011).

In order to measure the coolant level in the pressurizer in presence of the ship motions and inclination, instrumentation reference lines ending in the center of the cylindrical body at the upper part of the steam bubble were adopted. This way, the errors in level measurement due ship inclination are minimized, being negligible for small angles. Fig. 5 shows a cut view of the pressurizer with the reference lines (US Department of Transportation–Maritime Administration–Office of Ship Disposal, 2011).

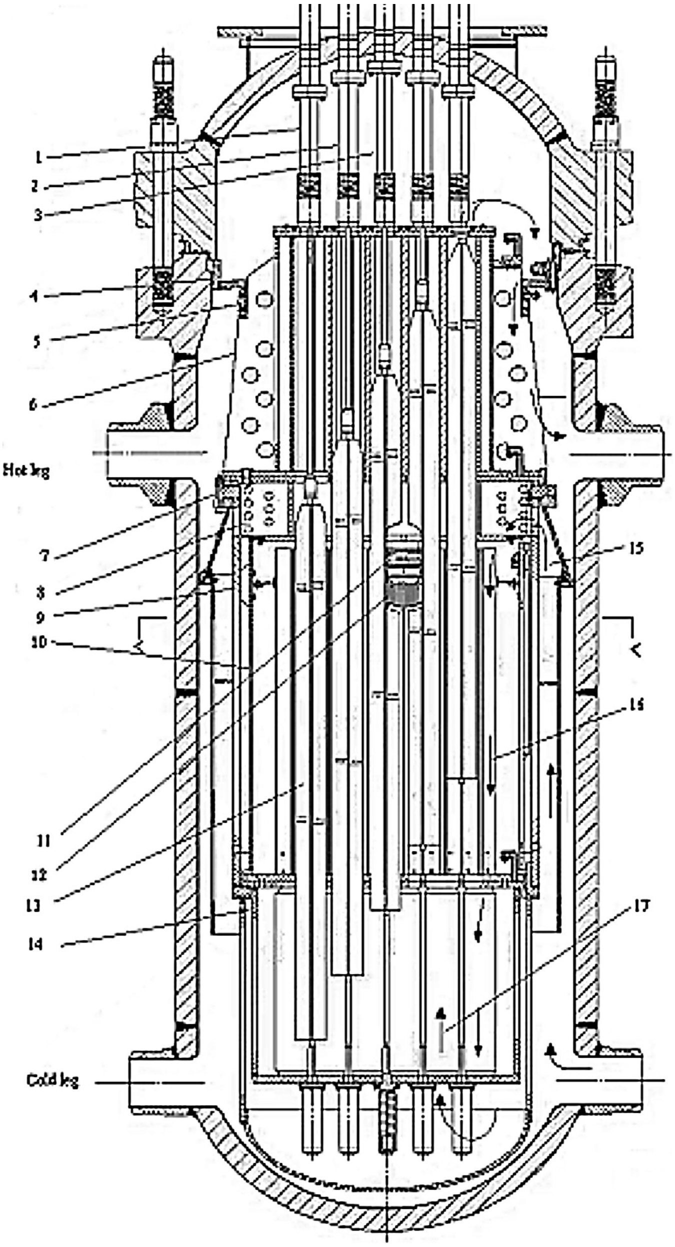


Fig. 2. NS Savannah core internals. 1, 2, 3 – Control rod inner sleeve; 4 – Belleville spring (reactor head closure); 5 – Belleville spring (upper flow baffle); 6 – upper flow baffle; 7 – connections to core baffle for support shield; 8 – upper grid plate; 9 – core support shield; 10 – inner thermal shield; 11 – spring coupling (hold down) for upper fuel element; 12 – fuel pins in fuel element; 13 – control rod; 14 – lower flow baffle assembly; 15 – first pass flow; 16 – second pass flow; 17 – third pass flow.

3. NS Otto Hahn

In 1962, the German company GKSS ordered a nuclear ore carrier at the shipyard “Kieler Howaldtswerke AG”. The advanced pressurized light water reactor was chosen for the propulsion of this first German nuclear merchant ship. The design of the first core was not optimized due to uncertainties in some properties of the core materials. It was desirable to obtain experience with the first core as early as possible and use it in designing the second core. The operation of the second (more advanced) core should provide information for

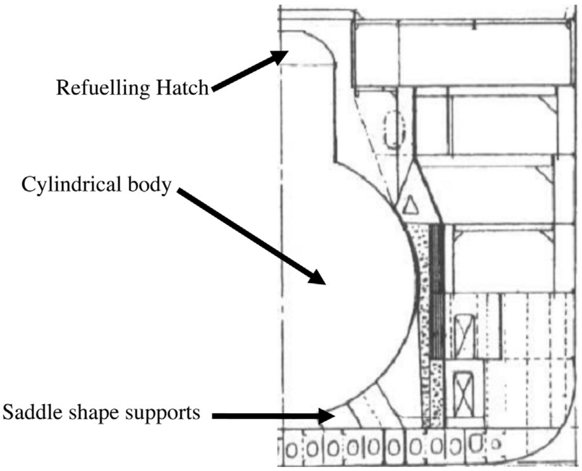


Fig. 3. NS Savannah containment.

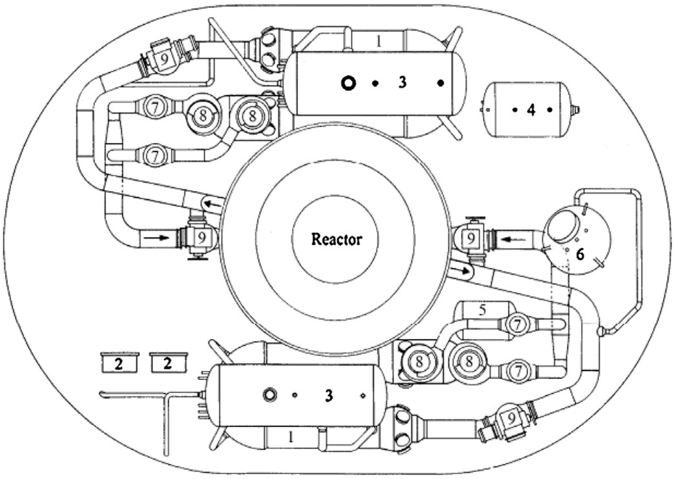


Fig. 4. NS Savannah arrangement. 1 – Steam generator U-tube bundle; 2 – let down cooler of primary purification system; 3 – steam generator steam drum; 4 – effluent condensing tank to collect and condense effluent from the relief valves; 5 – containment drain tank to collect radioactive liquid wastes; 6 – pressurizer; 7 – check valve to restrict reverse flow if a pump was not operating; 8 – primary pumps; 9 – gate valves to isolate one loop from primary circuit.

the design of future cores with lower fuel cycle costs (Rogan et al., 2008).

After 10 years of worldwide operation the nuclear research ship "Otto Hahn" was taken off duty in 1979. After having shipped 650,000 nautical miles and having used two cores of fuels, the research purpose of the ship was fulfilled and the owner, the state company GKSS, decided to remove the whole nuclear drive assembly which was placed amidships in three compartments. The dismantling concept aimed to release the ship out of regulatory control – compared with the principle "green meadow" – to have it available for further use after having installed a diesel engine.

There were some regulatory issues, like many ports refusing access to this ship on grounds of nuclear risk. This created serious limitations to the routes available to this ship. This fact together with the high operational expenses, led to the early removal of the core.

The NS Otto Hahn was equipped with a compact pressurized water reactor especially built for ships, with steam generators and coolant pumps integrated into the reactor pressure vessel; all arranged in a tank which formed the reactor shield, Fig. 6, adapted from Bruens (1981). The pressurizer was contained in the reactor pressure vessel and it was self-pressurized, working at hot leg saturation pressure. The three steam generators were once through, counter current helical coil type, with tubes composed of NiCrl6Fe8 alloy. The thermal power was 38 MWth. The second core worked with the following parameters: core outlet temperature of 269 °C; core inlet temperature of 258 °C; primary mass flow of 653 kg/s; secondary steam pressure of 3 MPa; secondary mass flow of 17.78 kg/s; secondary steam temperature of 267 °C (33 °C superheating); and feed water inlet temperature of 185 °C (Bruens, 1981).

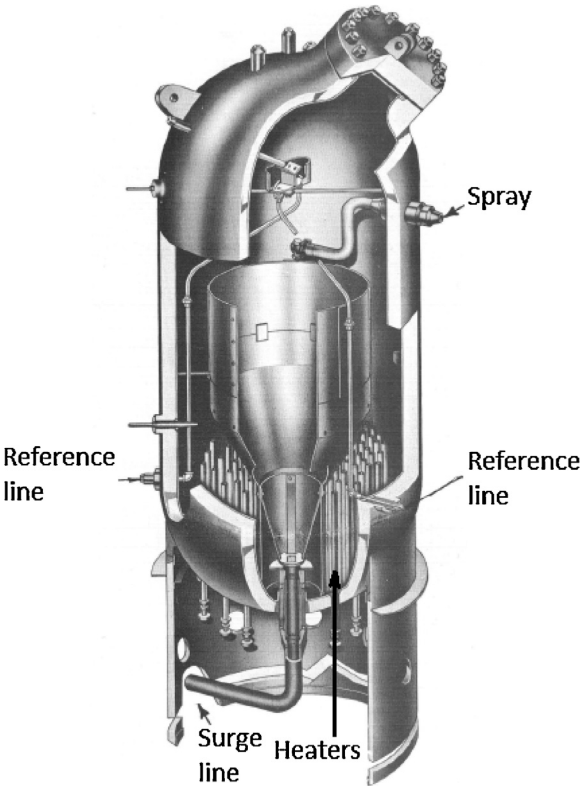


Fig. 5. NS Savannah pressurizer cut view.

The power conversion system had a turbo mechanical architecture with high and low pressure turbines, as shown in Fig. 7 adapted from Von Dobschuetz (1983).

This unit was shielded in a way that the containment could be entered even during operation. The nuclear area was divided in three main compartments. In the left compartment was located the reactor coolant system including the coolant pumps and the heat generators. In the right compartment was the spent fuel pool, and in the middle compartment there were other service equipment like nuclear auxiliary systems, hot workshop, laboratories, changing room and personnel airlock, shown in Fig. 8 (Von Dobschuetz, 1983).

The core consisted of twelve square and four corner fuel elements. A square fuel element consisted of 17 × 17 mesh with 289 spaces filled with four structure rods (to keep the spacers at constant distance from bottom support plate), 32 guide tubes for control rods and 253 fuel and burnable poison pins. The schematic view of the core and the arrangement of the fuel elements are shown in Figs. 9 and 10 (Rogan et al., 2008). The corner fuel element consisted of 12 fuel pins, 2 fuel pins filled with UB_4 (shown as "u" at Fig. 10), 4 fuel pins with central core made of B_4C shown as "G" at Fig. 10. It is interesting to note that some fuel rods employed fuel pellets with dishing (geometrical feature to accommodate thermal expansion) and some did not adopt dishing. Fig. 10 shows the distribution of the two types (with or without dish) of fuel rods.

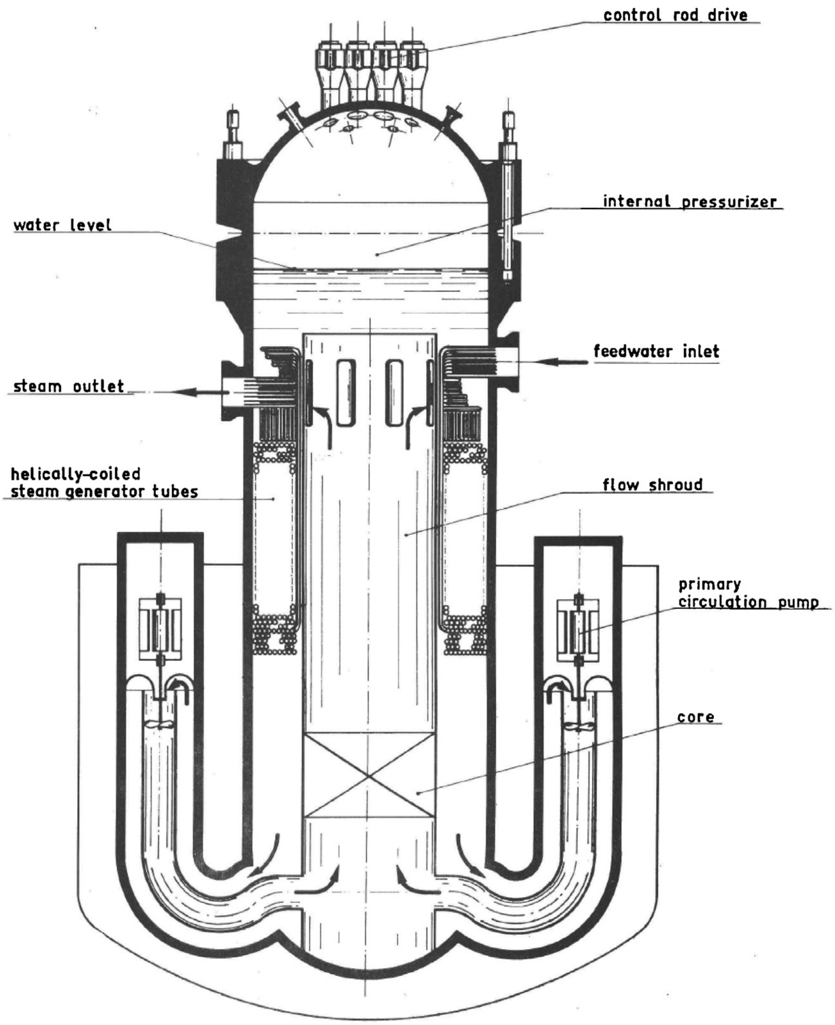


Fig. 6. NS Otto Hahn primary loop.

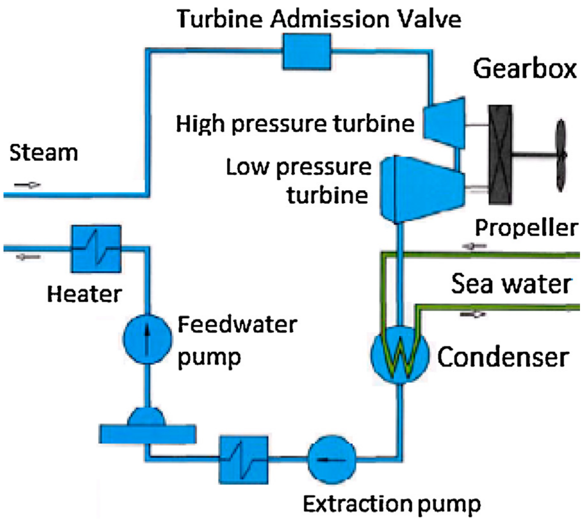


Fig. 7. NS Otto Hahn secondary loop.

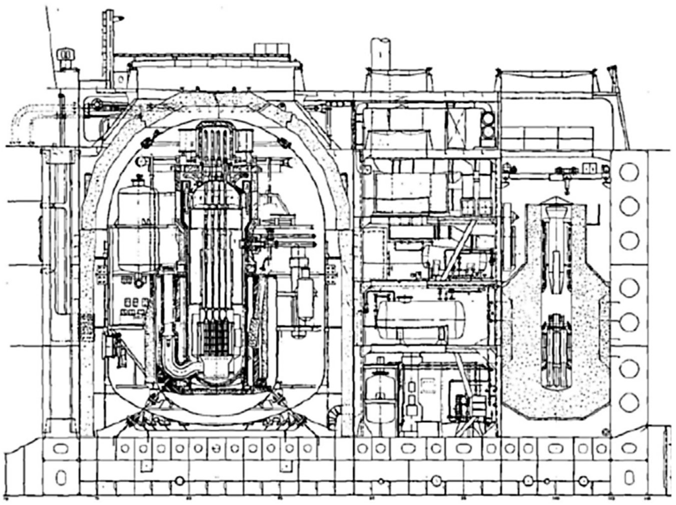


Fig. 8. NS Otto Hahn nuclear area.

Each control rod cluster assembly consisted of 32 control rods. The arrangement of control rods is depicted in Fig. 11. Each control rod was composed of B_4C and had a length of 730 mm (Rogan et al., 2008).

4. NS MUTSU

The Japan Atomic Energy Research Institute managed the construction of a prototype commercial ship for transporting special cargos and crew training. It was decided to commission the hull to

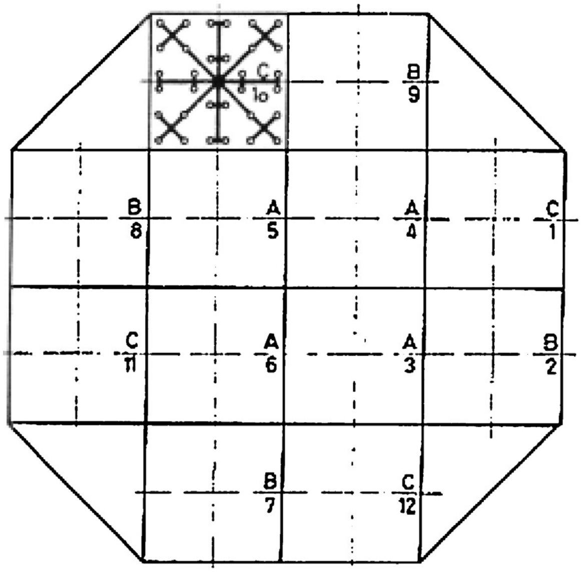


Fig. 9. NS Otto Hahn reactor core arrangement.

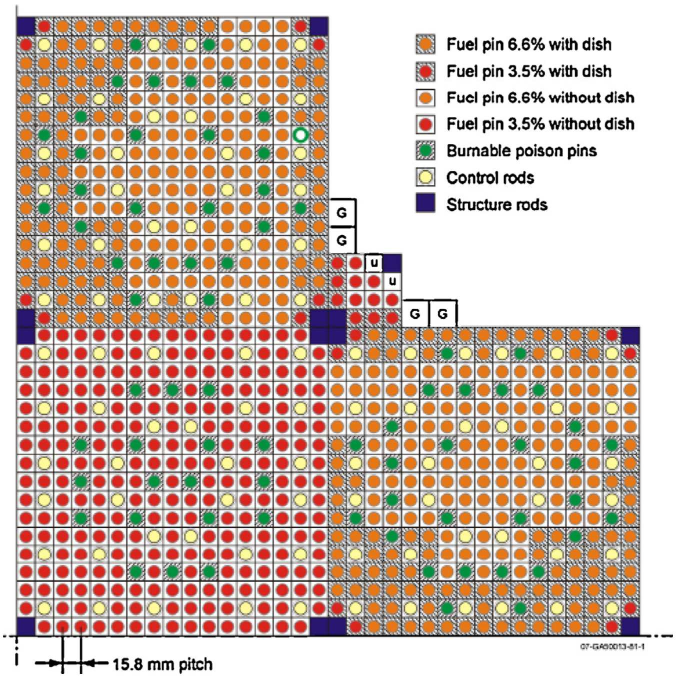


Fig. 10. Detailed one quarter of core view.

Ishikawajima-Harima Heavy Industries Co., Ltd. and the reactor to Mitsubishi Atomic Power Industries, Inc. The general layout of this ship is shown in Fig. 12 (Nakao, 1992).

The Mutsu nuclear reactor was rated at 36 MW and it had a core with 32 fuel assemblies. The 12 inner assemblies had ^{235}U enrichment of 3.24% and the 20 outer assemblies had enrichment of 4.44% (Fig. 13) (Shimooke et al., 1979).

Each fuel assembly was composed of an 11 × 11 square lattice of 112 fuel rods and 9 burnable poison rods, as shown in Fig. 14 (Shimooke et al., 1979). The fuel rod was made by inserting UO$_2$ pellets in the stainless steel cladding tube of outer diameter 10.53 mm and active length 1040 mm. The burnable poison rods were also built by inserting boron-silicate glass into tubes of same size of a fuel rod.

The vertical configuration is illustrated in Fig. 15. The poison part of the burnable poison rods is only 625 mm long, leaving upper and lower part without poison. The fuel assembly is bound by three clips of 38 mm between the top and bottom tie-plate. The control rods are cruciform and made of Ag–In–Cd alloy absorber and the zircaloy-2 follower. The core reactivity can be only controlled by the control rods during the reactor life (Shimooke et al., 1979).

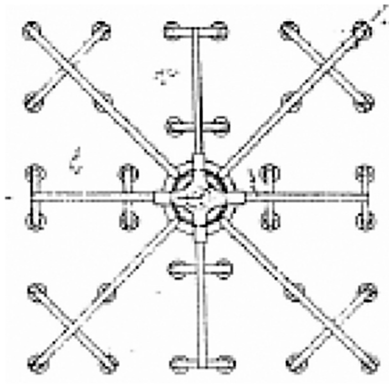
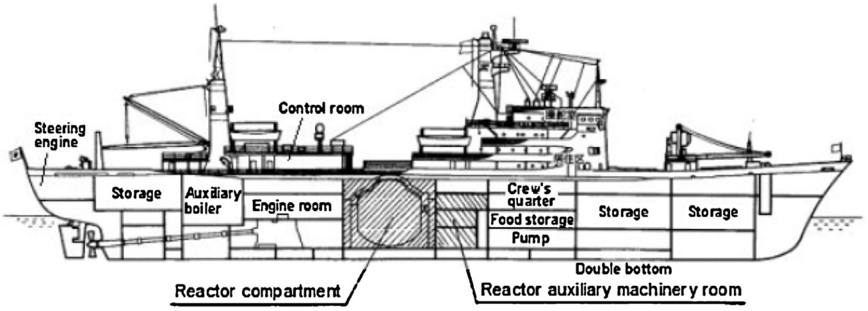


Fig. 11. Control rods cluster.



Purpose: Prototype
Length overall: 130 m
Molded breadth: 19 m
Molded depth: 13.2 m
Draft: 6.9 m

Gross tonnage: 8240 t
Output of main engine: 10000 horsepower
Maximum speed: 32 km/h
Normal speed: 30 km/h
Auxiliary power: 18 km/h

Reactor: Pressurized water reactor
Thermal output: 36 MW
Nuclear power: 145000
Cruising distance: NM (Under contemplation)
Crew capacity: 80

Fig. 12. Nuclear powered ship Mutsu.

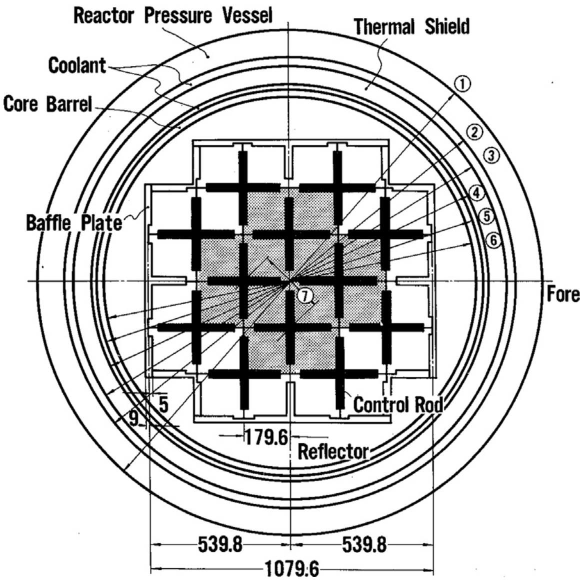


Fig. 13. NS Mutsu core configuration.

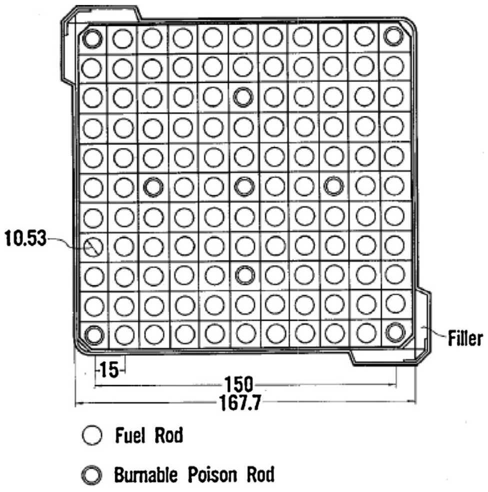


Fig. 14. NS Mutsu fuel assembly configuration.

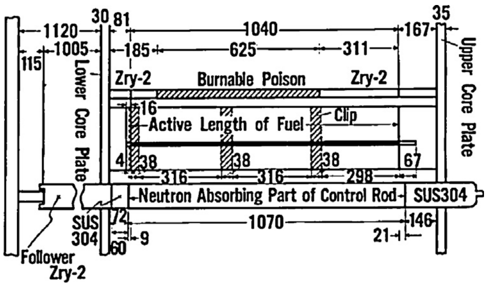


Fig. 15. NS Mutsu core vertical configuration.

The nuclear containment was a vertical cylinder with an inner diameter of 10 m and a height of 10.55 m. The internal pressure design was 1.25 MPa at 189 °C and the external design pressure was 0.3 MPa. On the bottom of the vessel, there were two balance valves which opened in case of ship sinking in order to prevent containment collapse. In the first version, the primary shielding structure consisted of an upper part (1 m thick concrete) and a lower part (multilayer cylindrical tank composed of iron and water). The primary shielding was sized to allow access to the reactor containment vessel in 24 h after reactor shutdown. The secondary shielding was composed of: 1000 mm thick concrete structures (density 2.3–3.4 g/cm^3) on the surrounding bulkheads and on the platform deck; 190 mm thick lead and 150 mm thick polyethylene on the upper part of the reactor containment vessel; double bottom water tank under the secondary concrete shielding (Oi and Tanigaki, 1969).

A series of extensive shield mockup experiments were performed from 1965 to 1967 in connection with the final design of the First Nuclear Ship in Japan. They included mockups of the primary shielding both in radial and in sloping upwards direction, secondary shield samples with cylindrical penetrations and samples having gaps between shield blocks (Kawai and Kataoka, 1969).

A design description of NS Mutsu reactor and secondary loop may be seen in Fig. 16 (Sato and Egusa, 1969). The reactor coolant system was pressurized at 11 MPa, the primary coolant mass flow was 500 kg/s, the core inlet temperature at full load (36 MWth) was 271 °C and its outlet temperature was 285 °C. The steam generators provided saturated steam at 4 MPa at full load (Sato and Egusa, 1969).

The hull was started in 1968 and finished in 1970. The reactor was completed on 1972, but when the officials announced there would be a low power test within the bay, the local fishermen and inhabitants protested against it. After negotiations, the government, the Japan Nuclear Ship Development Agency and the local community agreed to test the ship away at outer sea in 1974. Even so, when the ship left harbor, there were protests. At outer sea, when the reactor attained 1.4% of full power, it was detected an increase in fast neutrons radiation escaping the nuclear shielding.

The mass media reported this incident as “Nuclear powered ship Mutsu leaked radioactivity”. Concerned about the dangers to community and fishing industry, the local authorities refused to allow the ship return to harbor.

The radiation leak was caused by lack of experience on shielding design. Although Westinghouse Electric Company (US) had reviewed the design and warned about the possibility of streaming, the designer did not correct the original design. Another aspect is a part of the shielding was designed by the hull supplier and another part by the reactor supplier. The result was a lack of integrated verification of shielding efficiency (Nakao, 1992).

This design error had great repercussion because of the conceptual error of diffusion of radioactivity instead of radiation leak (Nakao, 1992). The country feared contamination of seafood, generating bitter protests and general distrust. It took a long delay to persuade harbor authorities to allow the ship to berth.

The government created the Mutsu Radiation Leak Investigation Commission to investigate the event and a report was submitted in 1975. While reporting issues on project organization, technology and contract, the commission evaluated positively that Mutsu satisfied the relatively high standards in the technological aspect and recommended some modifications (Nakao, 1992).

Mutsu underwent repairs from 1978 to 1982, improving the radiological shield in many aspects. The following changes were performed, Fig. 17 (Nakao, 1992): the new shield at the top was made of neutron absorbing serpentinite concrete; the new auxiliary shield was made of heavy concrete (it was previously made from lead and polyethylene); neutron absorbing chrysotile heat insulator was installed to the flange joint of the reactor pressure vessel; neutron absorbing zirconium hydride was added to the cap of the reactor pressure vessel; layers of polyethylene shield were added to the surface of the double bottom of the reactor containment (exterior); and a shield made of serpentinite concrete and silicon was added to the bottom of the reactor containment. The ship was completed in the beginning of 1991 and it was decommissioned in 1992.

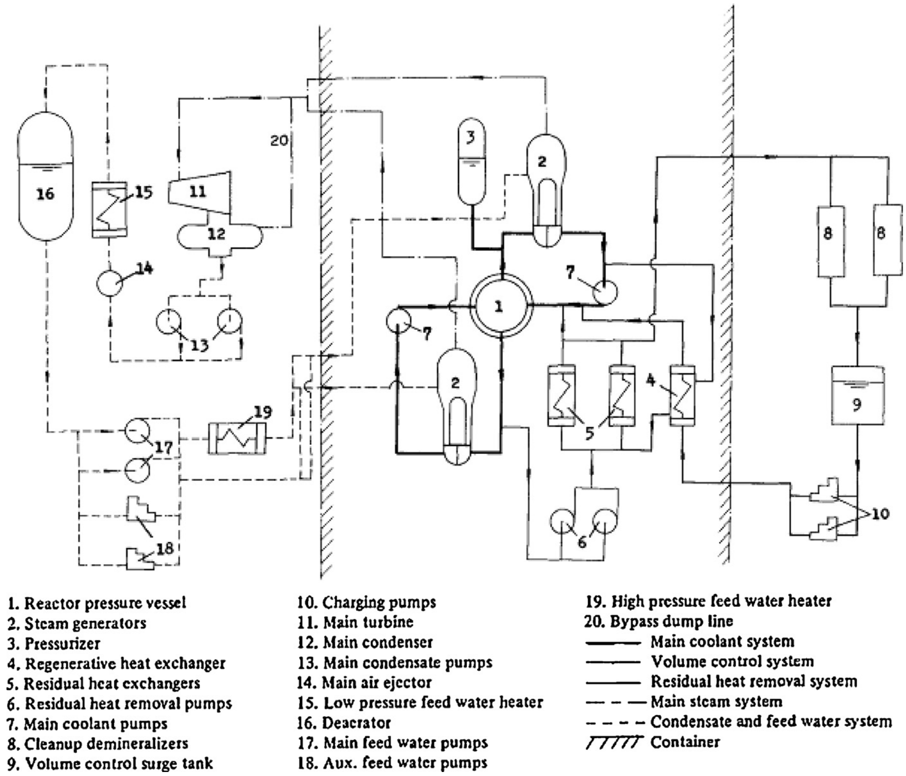


Fig. 16. Simplified diagram of NS Mutsu power plant.

For Nakao (1992), the project was affected by the negative publicity caused mainly by communication error. Another critical aspect was the division of the project between two companies, which generated integration and interface management issues.

5. NS SEVMORPUT

Historically, the development of the Russian Arctic has been closely linked to the development of the Northern Sea Route (in Russian, Severny Morskoi Put' or Sevmorput'), which was established by the Soviet Union in the 1930s. The route connects Russia's Atlantic and Pacific ports and has been in regular use since World War II. It is open for navigation from June to November and relies on extensive infrastructure, including the fleet of icebreakers and ice class cargo ships, aerial reconnaissance, meteorological stations, navigational aids, and port facilities. The route is a lifeline for many Arctic settlements that have their fuel, food and other resources brought to them by ships. The sea route is also used to move products of the mining, chemical, and wood processing industries in the Arctic regions of Siberia to Murmansk and other major ports with access to national and international transportation networks (Bukharin, 2006).

The development of a Russian marine reactor for civilian purposes started with the 90 MWth OK-150 power plant, which was the first plant used in the NS Lenin, which entered in operation in 1959. It was very favorable to employ nuclear icebreakers because of their huge power and autonomy, allowing communication with iced northern regions of Soviet Union. Later on came the second-generation 159–171 MWth OK-900 plants used in seven nuclear icebreakers starting in 1970 with a modification on NS Lenin. The third generation 135–171 MWth KLT-40 plants were employed in two nuclear icebreakers and in 29.4MWe NS icebreaking freighter Sevmorput, which became operational in 1988 (Reistad and Ølgaard, 2006).

However NS Sevmorput had an impeccable historic of services, many port authorities across Soviet Union denied access to the ship because of fear from nuclear accidents, mainly because of Chernobyl events.

The fuel elements are of the cluster type, with 53 fuel pins with an outer diameter of 5.8 mm. The heat transfer area of the

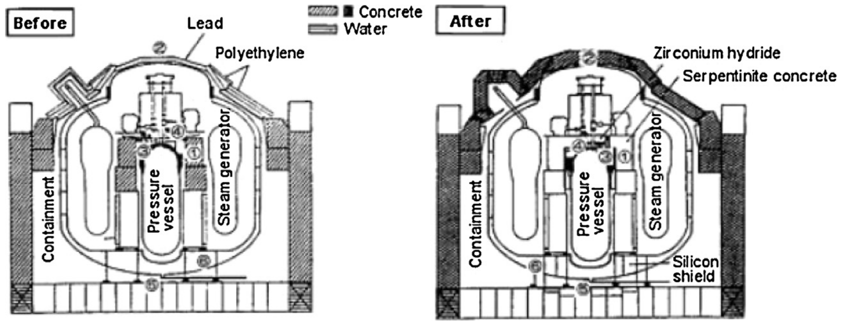


Fig. 17. Changes in NS Mutsu radiological shielding.

Table 3
Core and fuel data for KLT-40 of NS Sevmorput.

Parameter	Value
Reactor power	135 MWth
Core height	1 m
Core diameter	1.21 m
Mass of U-235 in core	150.7 kg
U-enrichment	90%
Number of fuel elements	241
Fuel element lattice type	Triangular
Fuel element lattice pitch	72 mm
Shroud, outer diameter	60 mm
Number of fuel pins	53
Fuel pin lattice pitch	7.2 mm
Fuel pin diameter	5.8 mm
Cladding material	Zr-alloy
Fuel material	U–Zr-alloy

core is 233 m^2. The spacing of the fuel pins in the element is 7 mm. The cluster of fuel pins is surrounded by a zirconium alloy shroud with an outer diameter of 60 mm. The fuel material is a uranium–zirconium alloy, and the uranium is 90% enriched. The total amount of uranium in the core is 167 kg (150.7 kg U-235). The cladding is a zirconium alloy. The fuel elements are also provided with burnable poison pins containing natural gadolinium. Table 3 (Reistad and Ølgaard, 2006) presents a summary of core and fuel data of KLT-40 employed at NS Sevmorput.

The operating period for Sevmorput is 10,000 effective hours. This presumably means that the achievable burn-up is 56,000 MWd (Reistad and Ølgaard, 2006).

The power level of the reactor is controlled by regulating the amount of feed-water. This is possible due to the negative temperature coefficient of the reactor, which assures self-regulating nuclear power generation. The reactivity is controlled by a system of shim and scram rods. The scram system consists of four banks of scram rods, moving in sleeves in 16 fuel elements. The scram rods are provided with accelerating springs to ensure rapid injection of the rods in case of emergency. The shim system consists of five rod-banks. Further, to ensure reactor shutdown in case of emergency, an aqueous solution of cadmium nitrate may be injected into the coolant.

The primary shield consists of consecutive steel-water layers. At the top the reactor vessel is provided with a concrete shield. Ships using KLT-40 plants are provided with containment systems so that any release of radioactive material from the primary system would remain inside the containment. Should the vessel sink, valves in the wall of the containment would stay open as long as the outside pressure was higher than that inside, thereby flooding the containment and preventing its destruction and release of radioactivity. Additionally, there is a pressure suppression system. With a release of steam inside the containment, pressure will increase. If the pressure rise exceeds about 0.05 MPa, a valve will open and the air-steam mixture will be led down through a water pool whereby the steam is condensed and the pressure reduced.

The coolant enters the reactor vessel at the top, flows downwards through the reflector/thermal shield, up through the reactor core and from the top of the reactor vessel to the steam generator. Then, the coolant flows through the canned circulation pump back to the reactor. The design is very compact, completely welded with a tube-inside-tube arrangement. This way, the length of the piping and the number of components of the primary circuit is kept to a minimum, reducing the risk of leakage. The reactor vessel is clad with a stainless steel layer. The thermal shield consists, in the radial direction, of steel-water layers and, at the top above the vessel lid, of a concrete shield. The core height is 1 m and the diameter 1.21 m. The 241 fuel elements are arranged in a triangular lattice with a spacing of 72 mm. The fuel elements are placed in a removable insert or basket inside the reactor vessel, and movement is prevented by fixing them both at the bottom and at the top. Fig. 18, adapted from Reistad and Ølgaard, (2006), gives a vertical cross-section of the reactor.

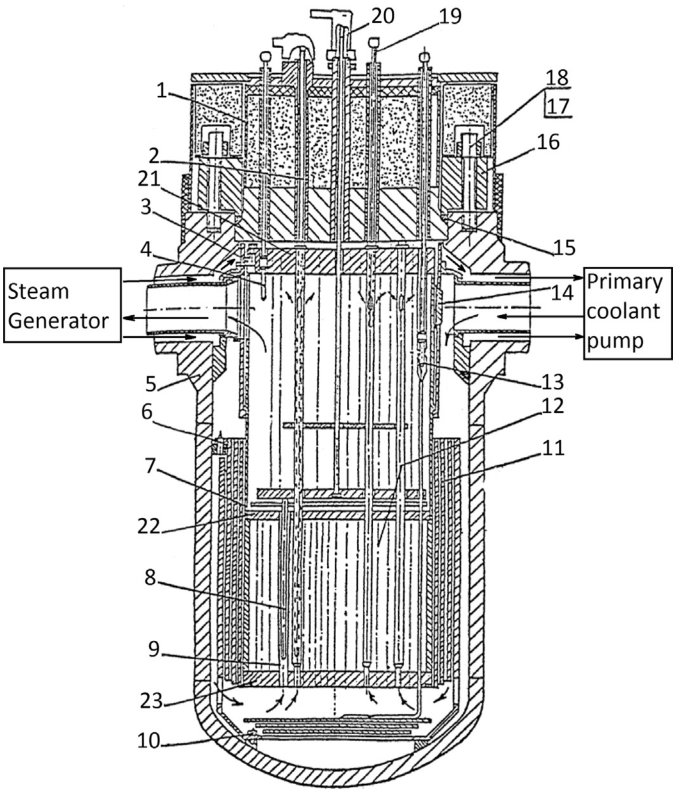


Fig. 18. KLT 40 layout. 1 – Reactor cover; 2 – emergency protection rod; 3 – anchor bolts; 4 – temperature sensor; 5 – reactor vessel; 6 – side screen attachment studs; 7 – withdraw able unit; 8 – reactivity shin rod; 9 – guide pipe of shin rod; 10 – side screen attachment stud; 11 – side screen shell; 12 – core; 13 – temperature sensor; 14 – separating shell with plug; 15 – gasket; 16 – pressure flange; 17 – nut; 18 – main joint stud; 19 – resistance thermometer; 20 – drive rod of withdraw able unit; 21 – upper plate of withdraw able unit; 22 – medium plate of withdraw able unit; 23 – lower plate of withdraw able unit.

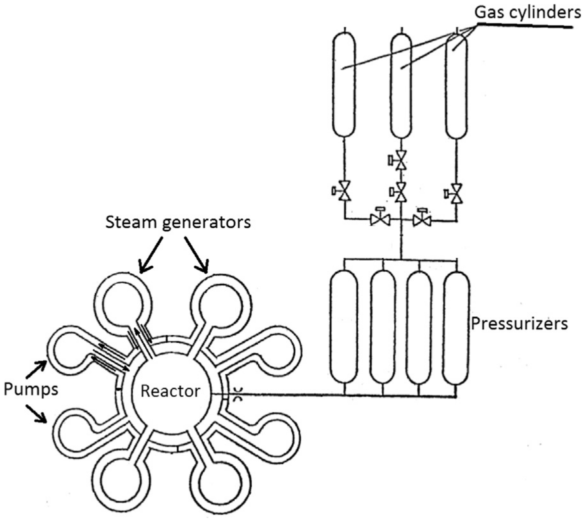


Fig. 19. KLT-40 reactor coolant system.

Fig. 19, adapted from Reistad and Ølgaard, (2006), shows the primary system. The reactor is provided with four cooling loops, each of which contains one steam generator and one circulation pump.

The pressure in primary system is controlled by a gas pressurizing system connected to four pressurizers. This system is based on injection/discharge of gas. The coolant inlet temperature is 278 °C and outlet temperature is 312 °C and the primary system pressure is 13 MPa. The temperature and pressure of the steam leaving the steam generator is 290 °C and 4 MPa, respectively. There is an emergency cooling system, but in addition, the reactor can run by natural circulation at 25–30% of full power.

The project was organized by Baltiiskiy Zavod, in cooperation with Wartsila Marine Shipyard in Finland. The conventional portion of the ship was built in Finland while the reactor and turbine equipment was installed at the Baltiiskiy Zavod plant in St. Petersburg.

6. Technical issues

In the case of NS Mutsu there were clearly interface management issues because the design and construction was commissioned for two different companies. This led to shielding problems because nobody took responsibility for the whole.

Another issue was the production of a great amount of radioactive waste in the NS Savannah, which was solved with minor changes.

All projects except NS Sevmorput had requirements definition problems. They were demonstrators of nuclear power, however they did not took into account economic feasibility along operation and capital costs. Therefore, even if they were, at the end, technically successful, they were abandoned because people then in power find it more profitable to drop the project. It must be noted that because of high capital costs, only huge and power intensive ships (like Panamax and Post-Panamax container ships) may be competitive running on nuclear power, which means thermal powers in range of hundreds of megawatts, not in tens of megawatts like NS Savannah, NS Otto Hahn and NS Mutsu.

In the case of NS Savannah, whose design was outdated because the advent of container ships, it can be observed a lack of pragmatism on the project, which means, to have continuity, it must be profitable. Money was spent in luxury decoration and a space was dedicated to passengers. Exaggerated resources were dedicated to nuclear containment and shielding if compared with modern submarines which provide a shielding so efficient that submariners are less affected by radiation than people at beach.

May be such degree of conservatism was led by a lack of prototypes, always adopted in case of military naval reactors. However, such prototypes should have smaller (scaled size) powers in order to profit on lesser footprints and safety requirements–thermal powers below 10 MW.

7. Social issues

Even if some initiatives in the naval nuclear reactors had some beautiful ideals and some dreams about economic side in a long term objective, the most important drive for continuity of a given project is the economical factor.

It is interesting in case of nuclear merchant ships except NS Savannah that public perception about nuclear safety is quite different from the military vessels which typically find little resistance from local port authorities.

It may be explained by the typical collective resistance against new technologies. In case of military vessels and the NS Savannah which are quite well known for a long time, people got used to the idea of naval reactors and accepted the vessels without much mistrust. Besides that, the operational nuclear safety records in many nuclear navies provided public confidence.

Another aspect, quite understandable, are the public trauma with huge nuclear accidents, like Chernobyl which caused protests against the presence of NS Sevmorput in some ports, and nuclear strikes in Japan which made the radioactivity matter something like a taboo and precluded the free operation of NS Mutsu.

In case of NS Mutsu, which was a project developed by bureaucrats without a public relations concerns, the outburst of protests against criticality tests were a surprise to officials. This shows this kind of project needs previous dialogs with local population, open discussions with experts not directly related to the project and prepare in advance a culture about risks and advantages of nuclear power.

Last but not least, trust is difficult to build and easy to be destroyed. It is too naïve to imagine information flows only in formal ways. When a given project has safety problems, the internal public will necessarily be aware of that. Those people have family and friends which in turn propagate bad news very fast and, typically, in a distorted way. Therefore, besides working on external public acceptance, it is necessary to build confidence on internal public. This may be done with adequate formation, clear responsibility, transparency and external supervision.

8. Lessons learned

The first aspect is that naval propulsion is definitely feasible. All ships employed fuel rods and except for NS Sevmorput, they used low enrichment uranium. The first impression is very important and because it is difficult to achieve a complete success for a first project, prototypes are almost essential to build confidence.

The economic advantage is the base to keep a project running, which means cost effectiveness must be taken into account during the project. The only economically successful ship was NS Sevmorput which is a third generation of naval reactors produced in former Soviet Union. The first ship, NS Lenin, had many problems and had its reactor substituted. That is, there is a learning curve for the development. Furthermore, management is a problem, aggravated when more than one enterprise is involved in design, especially at the interfaces.

Military institutions and universities receive more credit than private enterprises, which means a joint venture involving military interests, university research and private enterprises profit should be a hard but steady way.

Last, but not least, the media plays an important role in acceptance and public perception is much affected by the possible gains – an additional risk must be compensated by a gain. The obvious gains for the public of use of nuclear energy must be made clear and misinformation must be minimized with education.

9. Conclusions

The nuclear energy is an alternative for merchant propulsion and it is theoretically economical for large and fast ships if architecture with low cost is employed.

The general public opinion need to be informed about risks and benefits of nuclear power in advance before resistance is formed.

Besides, the project management according to the best practices is the base for building confidence in internal public, which will allow building confidence on external public.

The expenses required to advance in the learning curve are too high to be absorbed by private investors. A solution is to have development and production costs shared with non-profit institutions like universities and armed forces.

The design of the reactor must take into account the possible market niches and markets trends to identify potential clients and have precise set of needs.

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