Naval Application of Battery Omnibus Reactor Integral System

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ABSTRACT

This paper presents design concepts of the first-of-a-kind engineering of the Nuclear Operated Vessel Adventurer (NOVA). NOVA is being designed with such novel concepts as a primary system Battery Omnibus Reactor Integral System (BORIS) using the lead (Pb) coolant, a secondary system Modular Optimized Brayton Integral System (MOBIS) employing the SCO_2 Brayton cycle, and an electric propulsion system Naval Application Vessel Integral System (NAVIS). An ultra-small, ultra-long-life, fast-spectrum reactor BORIS is being developed for a multi-purpose application such as naval power source, electric power generation in remote areas, seawater desalination, and district heating. NAVIS aims to satisfy special environment on the sea with BORIS using Pb in the primary system operated by natural circulation without pumps. BORIS is being designed to generate 22.2 MW_{th} for at least twenty consecutive years without refueling and to meet the naval nuclear system goals of compactness, safety, reliability and economics. NAVIS improves the economical efficiency resorting to the SCO_2 Brayton cycle for the secondary system. SCO_2 promises a high power conversion efficiency of the recompression Brayton cycle due to its excellent compressibility reducing the compression work at the bottom of the cycle and to a higher density than helium or steam decreasing the component size. Therefore, the SCO_2 Brayton cycle efficiency as high as 45 % furnishes small reactors with economical benefits on the plant construction and maintenance. To apply the progressive technology to ship, we adopted an electric propulsion system with high temperature superconducting (HTS) motor for propulsion system and employed a Small Water-plane Area Twin Hull (SWATH) having an innovative maneuverability. The electric propulsion system NAVIS provides NOVA with improved fuel and maintenance costs, flexibility of on-board space and reliability.

INTRODUCTION

Past civilian N.S. Savanna (80 MW_{th}), Otto-Hahn (38 MW_{th}) and Mutsu (36 MW_{th}) experienced stable operations under various sea conditions to prove that the reactors were stable and suitable for ship power source. Russian nuclear icebreakers such as Lenin (90 $MW_{th}\times 2$), Arukuchika (150 $MW_{th}\times 2$) showed stable operations under severe conditions during navigation on the Arctic Sea [1]. These reactor systems, however, should be made even more efficient, compact, safe and long-life, because adding support from the land may not be available on the sea. In order to meet these requirements, an innovative integral system NAVIS (Naval Application Vessel Integral System) is being designed with such novel concepts as a primary system Battery Omnibus Reactor Integral System (BORIS) using the lead (Pb) coolant, a secondary system Modular Optimized Brayton Integral System (MOBIS) employing the SCO_2 Brayton cycle and an electric propulsion system adopting a Small Water-plane Area Twin Hull (SWATH).

NAVIS is powered by BORIS. A lead (Pb) cooled multi-purpose fast-spectrum reactor BORIS is being developed at the Seoul National University [2]. BORIS is being designed to generate 22.2 MW_{th} for at least twenty consecutive years without refueling and to meet the Generation IV Nuclear Energy System goals of sustainability, safety, reliability, and economics. BORIS resorts to a proliferation-resistant nitride fuel of a high thermal conductivity with minor actinides (MA), and an open cartridge type core without individual subassemblies. BORIS adopts MOBIS using SCO_2 Brayton cycle for its power conversion [3]. SCO_2 promises a high power conversion efficiency of the recompression Brayton cycle due to its excellent compressibility reducing the compression work at the bottom of the cycle and to a higher density than helium or steam decreasing the component size. Therefore, the SCO_2 Brayton cycle efficiency as high as 45 % furnishes small reactors with economical benefits on the plant construction and maintenance. To help utilize advantages of BORIS and MOBIS, we adopted an electric propulsion system with high temperature superconducting (HTS) motor and employed SWATH for NAVIS. This paper presents basic design concepts of NAVIS for the first-of-a-kind engineering of the Nuclear Operated Vessel Adventurer (NOVA).

REACTOR SYSTEM

As coolant, sodium (Na) has a reasonably low melting temperature, but also features a low boiling point of 1151 K, which raises safety concerns to avoid unprotected transients leading to a coolant heat-up. Na also exhibits high chemical reactivity with water, water vapor and air. A Na leak and fire accident has stopped the operation of the Japanese MONJU reactor since 1995. In contrast to the chemically reactive Na, lead (Pb) has gained renewed interests in the western hemisphere since Russian experts had succeeded in using Pb in their fleet of nuclear submarines. The choice of Pb as the coolant is motivated on the one hand by its high boiling temperature of 2013 K. Pb is considered as a more attractive coolant option than Pb/Bi mainly due to its higher availability, lower price and lower amount of induced Po activity.

Albeit pure Pb has a melting temperature of 601 K, which narrows in the reactors operational interval to about 720-840 K, higher outlet temperatures will be eventually realized. Redundant electrical heaters are proposed to be introduced in order to avoid problems with freezing and blockages in fresh cores [4].

The BORIS design goal for simplicity dictates that the number of subsystems and the machinery adopted in the reactor system be less than that of, say, the conventional pressurized water reactors (PWRs). The goals are prerequisite to being competitive with the conventional engine of commercial ships.

All of the BORIS major primary system components such as fuel and core, six heat exchangers are housed in a reactor vessel. BORIS has no large piping and thus no possibility of any large-break loss-of-coolant accidents (LOCAs), no pressurizer and primary coolant pumps that are applied in PWRs. BORIS is conceptualized to be used as a main power and heat source for remote sites and ships, and also considered to be deployed for desalinization purpose. BORIS consists of modular components to be viable for rapid construction and easy maintenance, and adapts integrated heat exchanger system operated by natural circulation of Pb coolant without pumps to realize a compact reactor. Simplification in designing mentioned above renders BORIS highly reliable and transportable.

Integral Reactor Vessel

The reactor vessel and core are shown in Fig. 1. The effective layout of the primary components makes the reactor compact by installing most of the components inside the vessel. The Pb coolant flows upward via core, and goes down through the six heat exchangers inside the vessel. The integral design eradicates any potential LOCA in the primary system.

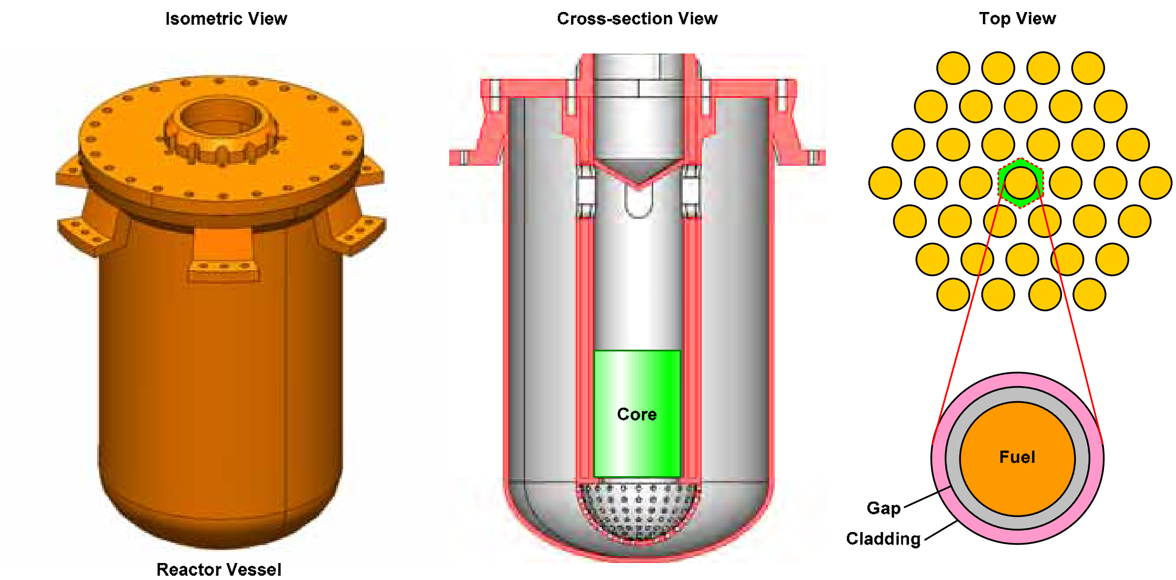

Fig. 1 BORIS Reactor Vessel and Core

Reactor Core

The reactor core is made up of 757 fuel rods without assemblies. The active core height is 0.8 m, and the core diameter is 0.9828 m. Thermal design requires that temperatures of the reactor core structures be maintained under certain criteria so as to prevent damage of fuel materials which can advance to severe situations such as clad rupture with ensuing fission product release, flow blockage and even meltdown of the core material. Accurate prediction of the core coolant and fuel temperatures is thus crucial in the process of core thermal hydraulic design.

BORIS uses a nitride fuel with Pb gap bonding and HT9 clad. Use is made of thermo-physical properties of $(U_{0.8}Pu_{0.2})N$ for the fuel pellet analysis. A finite element program is being written to perform thermal analysis for the single fuel rod in steady state with boundary conditions applied to the geometry.

Primary System

BORIS adopts an integrated heat exchanger system operated by natural circulation of Pb coolant without pumps to realize a compact reactor. BORIS utilizes proliferation-resistant nitride fuel with a high thermal conductivity and open cartridge type core without individual subassemblies. Under this condition, the major design parameters for the primary system of are presented in Table 1.

Table 1. Major Design Parameters for Primary System

Parameter	Value
Power Density (MW/m^3)	61.679
Mass Flow rate (kg/s)	1,276.32
Velocity in Core (m/s)	0.42
Input Coolant Temperature (K)	713.15
Temperature Difference (K)	120.0
Total Pressure Drop (Pa)	3,884
Thermal Center Difference (m)	2.45

Pressure drop in the reactor module is a key factor during primary system design because the thermal energy from fission is removed by natural circulation of the Pb coolant. Thus, the natural circulation flow rate and thermal center difference between the core and the heat exchanger is determined considering the friction and form loss of the elements.

The temperature difference between the core inlet and outlet is at least 120 K according to linked calculation with the secondary side conditions. Hence, the thermal center difference is determined to be 2.45 m. The reactor power is to be controlled by load-following-operation without an active reactivity control system, while a B4C-based shutdown control rod is to be equipped for an emergency condition [5].

Heat Exchangers

Six heat exchangers are equipped in reactor vessel as the heat sources of MOBIS. The operating conditions were listed in Table 2. The heat exchangers are independent of each other so that the thermal load of one heat exchanger is about 3.7 MW.

Table 2. Operating Condition for Heat Exchanger

	Primary		
	Pressure [MPa]	Temperature [K]	$\dot{m}$ [kg/s]
Inlet	0.1	833	212.72
Outlet	0.1	713	212.72
	Secondary		
	Pressure [MPa]	Temperature [K]	$\dot{m}$ [kg/s]
Inlet	19.9	663	18.8
Outlet	19.9	823	18.8

POWER SYSTEM

SCO_2 having a higher density than He or steam reduces the component size and compressor work at the bottom of the recompression Brayton cycle, increasing the overall cycle efficiency. It is thus crucial to optimize MOBIS and its major components affecting the overall cycle efficiency. The MOBIS efficiency was calculated to be 45% pursuant to the first law of thermodynamics. MOBIS consists of a 14.7 MW_{th} turbine, a 31.6 MW_{th} HTR, a 12.6 MW_{th} LTR, a 10.2 MW_{th} pre-cooler and 2.0 and 2.6 MW_{th} compressors. Entering at 19.9 MPa and 663 K, the SCO_2 leaves the in-vessel heat exchangers at 19.9 MPa and 823 K. The operating conditions and the SCO_2 flow scheme are illustrated in Fig. 2. The high thermal efficiency of MOBIS plays an important role in achieving the economics of BORIS [6].

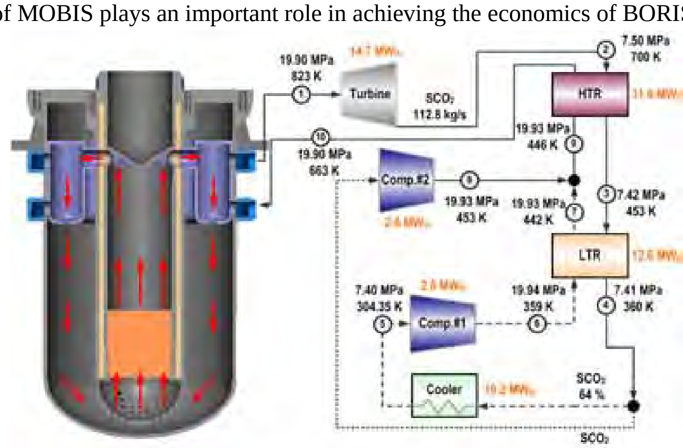

Fig. 2 Schematic Flow Diagram of BORIS and Calculated MOBIS Boundary Condition

The SCO_2 Brayton cycle has been not only adopted in the secondary loop of some Generation IV nuclear energy systems but also planned to be employed in the high efficiency power conversion cycles of the nuclear fusion reactors like the ITER and KSTAR. The reason for these welcomed applications is that the cycle can achieve the overall energy conversion efficiency as high as 45 %.

NAVAL APPLICATION

For the fast 60 years, many researches have shown the advantages of nuclear power propulsion with various applications such as military surface ship, submarine, ice breaker etc. These kinds of ships require to working for long periods of time on the ocean, where supply of fuel is complicated and sometimes impossible. NAVIS, innovative integral nuclear propulsion system using BORIS, will satisfy these requirements with a compact and simple design.

Reactor Vessel Auxiliary Cooling System (RVACS)

In the interest of the emergency core cooling system (ECCS), the RVACS of the NAVIS consists of the water-filled containment and containment water cooling system (CWCS). The main function of this safety system is to remove the core decay heat that causes a core flooding accident.

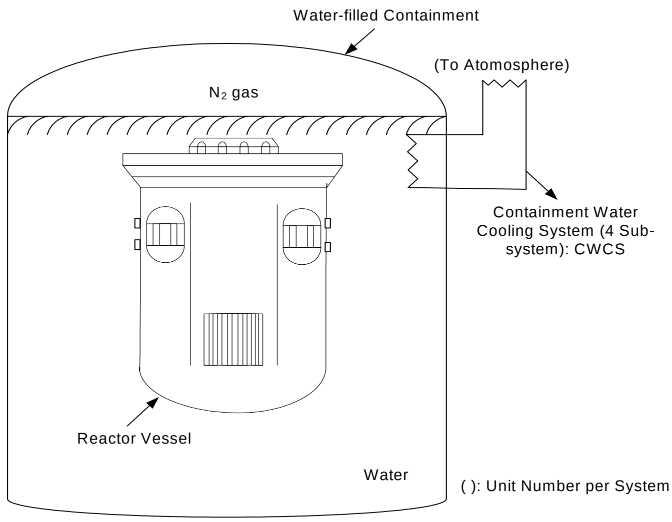

Fig. 3 Cross Section of the RVACS

The core flooding can be attained multiply because of the decay heat is transferred from the primary coolant to the water of containment through the wall of reactor vessel and from the water of the containment to the atmosphere through heat exchangers of CWCS. CWCS of heat-pipe type always transfers the heat from the containment to the atmosphere because opening valve isnt set. Therefore, the decay heat can be removed by circulation force with the RVACS and can handle the core cooling to achieve an adequate condition. The cross section of the RVACS is shown in Fig. 3. The beauty of this system is that it can cool the reactor passively without using moving parts. There is nitrogen gas to maintain pressure at the upper space inside the containment to avoid boiling of water in the containment [7].

The water-filled containment has a function of enclosing the area for prevention of radioactive material release to the surroundings as well as one of safety cooling system. In other words, the water has also a role of radiation shielding instead of the concrete shield. These make the BORIS advanced safety system simple and lightweight.

Electric Propulsion System Adopting SWATH

SWATH is an acronym meaning Small Water-plane Area Twin Hull. The water-plane is the horizontal plane cross-section of a ships hull at the water surface. SWATH ships typically have two submarine-like lower hulls completely submerged below the water surface. Above water, a SWATH resembles a catamaran. Its haunch areas are connected to each submerged hull by one relatively thin vertical strut. The longitudinal cross-section of each strut is somewhat streamlined to decrease wave-making resistance [8].

SWATH ships key advantages are: (1) ability to deliver big-ship platform steadiness and ride quality in a smaller vessel, (2) ability to sustain a high proportion of its normal cruising speed and (3) ability to keep the position on rough head seas. Because of these reasons, we adopted a SWATH type for NAVIS as shown in Fig. 4. Two motors for propulsion are situated in lower hull and linked up with a propeller through a thrust block. On the other hand, the reactor and two turbine generators are located in the deck.

For many years cathedral diesel engines were the propulsion method of choice, until developments in semiconductor technology during the 1970s and early 80s allowed variable speed drives to become commercially viable. Over the last decade much work has been carried out regarding the economic and technical viability of the electric propulsion ship.

The speed control of the propulsion motor is achieved by using variable speed drives, which allow a fixed frequency supply to be converted to a specific input frequency for the propulsion motor. This configuration has several major advantages over any other propulsion systems:

1. Improved fuel and maintenance costs, depending on vessel operational profile. This is particularly relevant when there is a large difference in the load demands of the hotel and propulsion systems.

2. Flexibility of on-board space through a propulsion motor positioned independently of shaft line without the need for a shaft line.

3. Increased reliability though a stable electric propulsion motor that has less repairing frequency than any other mechanical engines.

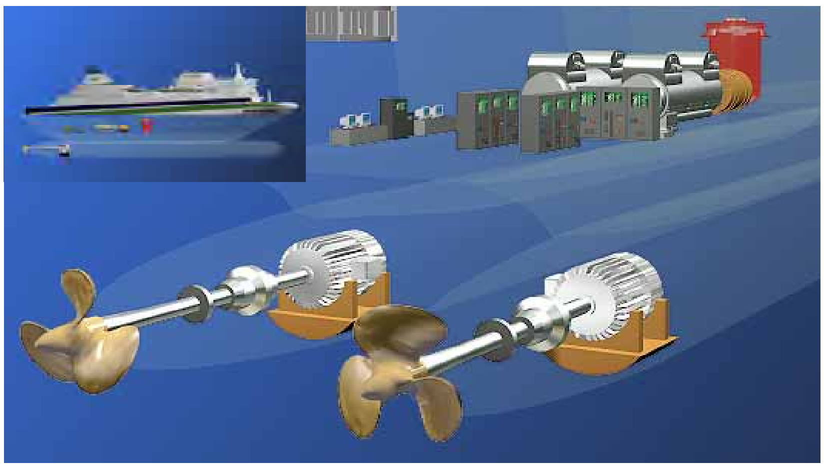

Fig. 4 General Arrangement of NAVIS

Ships today also tend to consume more electricity than did their predecessors. Integrated electric propulsion systems optimize ship operator's flexibility through the ability to only use the minimum amount of electricity generation equipment for a given operational scenario. It is because of advantages like these that nearly all cruise ships and many other ship types have made the transition to integrated electric propulsion systems.

One of the most promising of the technologies related to this major shift to electric ship propulsion is the development of high-temperature superconducting (HTS) wires for powering propulsion motors. The machines use rotor coils wound with HTS wires, which can conduct more than 150 times the electric current than copper wires of the same dimensions, with no resistance. These characteristics offer us the ability to design a more suitable electric propulsion motors that deliver much higher power density at higher electrical efficiency. Propulsion motor employing HTS wire are very compact in size and low in weight as compared with conventional electrical machinery, and operate more efficiently at all loads. These qualities make them easier to site in the ship, allows more modular ship construction, and reduces undesirable tradeoffs that face many ship designers [9].

Because of these reasons and to help innovative advantages BORIS and MOBIS mentioned above, we adopted an electric propulsion system with high temperature superconducting motor for propulsion system for NAVIS. high temperature superconducting (HTS)-based propulsion systems play an important role in achieving the goals of NAVIS. The overall schematic diagram of electric power system is shown in Fig. 5.

CONCLUSION

Past nuclear propulsion ship experienced stable operations under various sea conditions to prove that the reactors were stable and suitable for ship power source. These reactor systems, however, should be made even more efficient, compact, safe and long-life, because adding support from the land may not be available on the sea. So as to meet these requirements, innovative integral system NAVIS is being designed with such novel concepts as BORIS, MOBIS and electric propulsion system.

NAVIS is powered by BORIS. BORIS is being designed to generate 22.2 MW of thermal power at least twenty consecutive years without refueling and to meet the Generation IV nuclear energy system goals of sustainability, safety, reliability, and economics.

BORIS adopted the SCO_2 Brayton cycle system MOBIS for its power conversion. SCO_2 promises a high power conversion efficiency of the recompression Brayton cycle due to its excellent compressibility reducing the compression. NAVIS applied these innovative designs to the SWATH ship with electric propulsion that makes the ship to keep the position easily because of flexibility for repeated power changes.

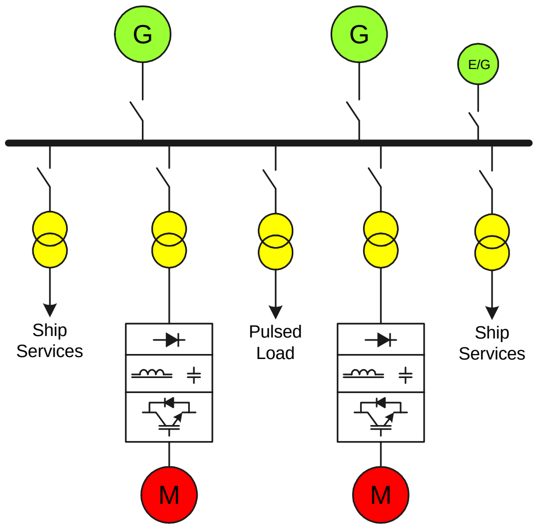

Fig. 5 Overall Schematic Diagram of Electric Power System

ACKNOWLEDGEMENTS

This work was performed under the auspices of the Center for Advanced Prototype Reactor Initiatives (CAPRI) as part of the Brain Korea 21 Program funded by the Korean Ministry of Education & Human Resources Development.

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