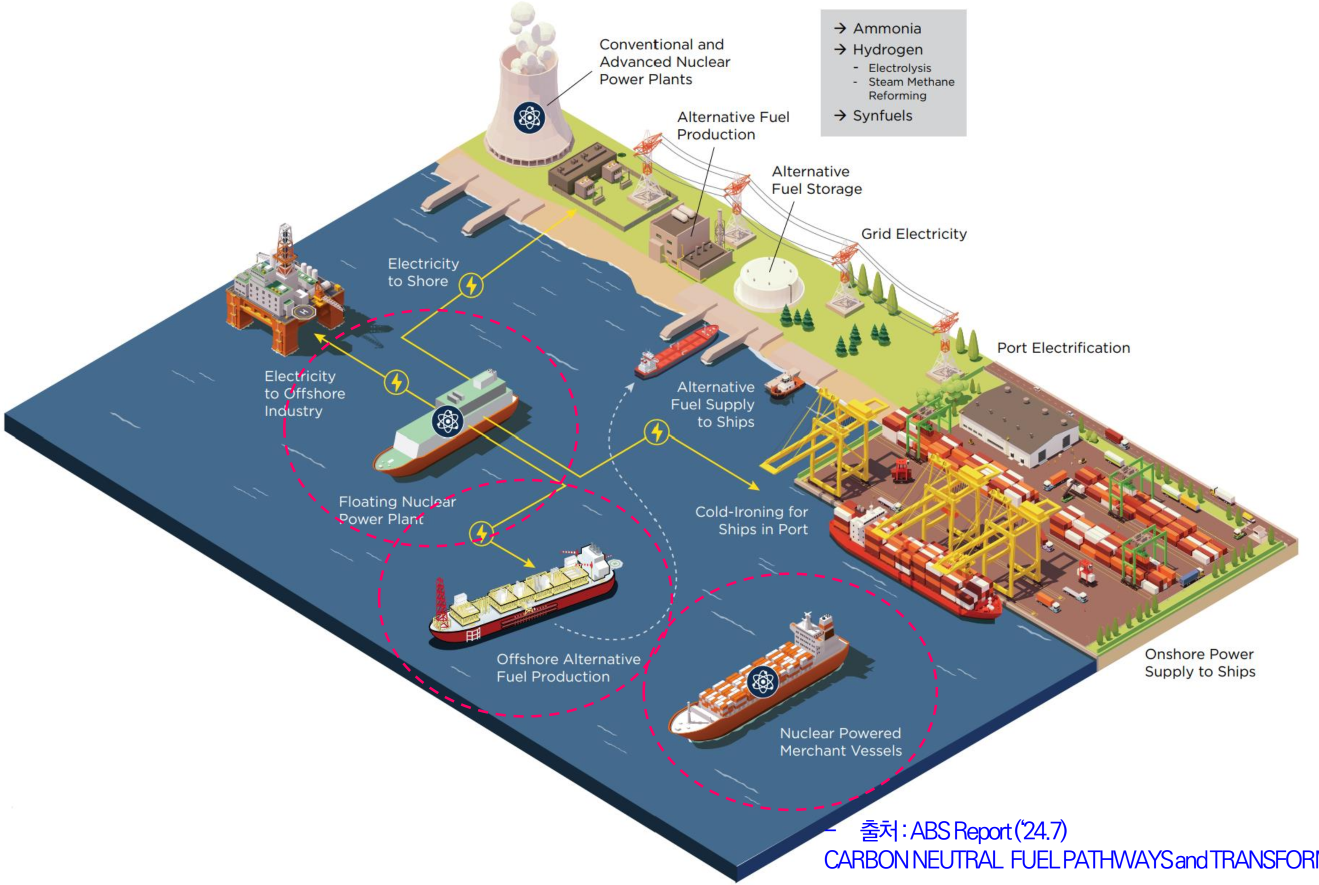
수냉각형 원자로 해양적용을 위한 기술적 제도적 이슈

삼성중공업 조선해양연구소

김종원 프로

2024. 10.

해양 원자력 Value Chain



- 출처 : ABS Report ('24.7)
CARBON NEUTRAL FUEL PATHWAYS and TRANSFORMATIONAL TECHNOLOGIES

경수로 기반 조선해양 원자력 제품

Akademik Lomonosov (러시아)

- ✓ KLT-40S (35 MWe) 원자로 2기 탑재
- ✓ 부유식 해상 원전을 위한 반일체형 경수로
- ✓ Pates Akademik Lomonosov – Google 지도

Project 22220

- ✓ 오래된 쇄빙선을 대체하기 위한 원자력추진 쇄빙선 건조 사업
- ✓ RITM-200 경수로 탑재, 총 5개의 쇄빙선 시리즈

. 1호 아르티카(Arktika) (2020), 2호 시비르(Sibir) (2022)

3호 우랄(Ural) (2022), 4호 야쿠티아(Yakutia) (2024 예정)

5호 추코트카(Chukotka) (2026 예정)

- Sibir호

경수로 기반 조선해양 원자력 제품

▪ 경수로(PWR) 기반 원자력 상선

✓ NS Savannah(美), Otto Hahn(獨), Mutsu(日) 및 러시아 쇄빙선




	Savannah	Otto Hahn	Sevmorput	Yamal
Nationality	USA	Germany	Russia	Russia
Purpose	Bulkcarrier	Orecarrier	Containership	Ice Breaker
Service Time	1962~1972(11y)	1968~1979(12y)	1988~Present(33y)	1992~Present(29y)
Installed Power	74 MWth Babcock & Wilcox	38 MWth Babcock & Wilcox	136 MWth OKBM	63 MWth OKBM
LxBxD, m	180 x 23.8 x 18	172 x 23.4 x 15	260 x 32 x 18.3	148 x 30 x 17.2

✓ 기술적 능력 확인, 경제성 및 정치적 문제

✓ **핵연료 재장전, 사용후핵연료 문제**

삼성중공업 : 해양 용융염원자로 제품 개발 협약

- 삼성중공업 – 한국원자력연구원 MOU (‘21. 6월)
  - ✓ **용융염(염소염) 원자로** 기반 제품 협력
    - 부유식 해양 원자력 발전 플랜트 특화 개념 설계
    - 원자력 추진선 특화 계통 개념 설계
    - 원자로 인허가 및 해양 원자력 제품 법규 기준 개발
    - 비즈니스 모델 도출을 통한 경제성 평가

- 삼성중공업 – Seaborg Technology MOU (’22. 4월)
  - ✓ **용융염(불소염) 원자로** 기반 제품 협력
    - ‘부유식 해양 원자력 발전 플랜트’ 제품 개발
    - 최대 800 MW급 발전설비 및 수소/암모니아 생산 모듈 개발

원자력 해양 이용

해양 적용에 유리한 원자로 노형

- 원자력추진선, 부유식(착저식) 원전 등의 비즈니스모델에 따른 분석
- FHR, MSR의 특징 반영
  - 상압, 고온 조건 → 해양 조건에 유리

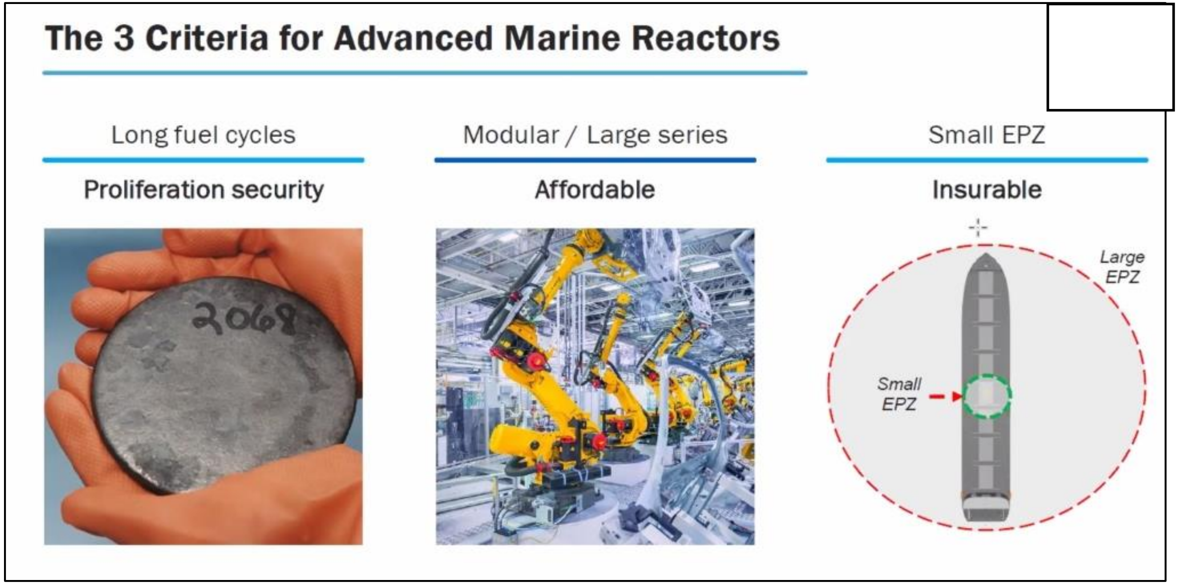
Reactor Type	Fixed land/ coast	Fixed offshore, independent only	Fixed offshore w/ onshore grid coupling	Self-propelled vessel, local	Self-propelled vessel, international
Light Water Reactor (LWR)	Already exists on land	Low temperature limits efficiencies for synthetic fuel production	Will need heat augmentation	Already exists for Naval/ Government applications	Already exists for Naval/Government applications
Sodium Fast Reactor (SFR)	Under development	Sodium-water interactions	Sodium-water interactions	Sodium-water interactions	Sodium-water interactions
Lead Fast Reactor (LFR)	Least mature technology in the West	High temperature, Lead (Pb) shielding	High temp, Lead (Pb) shielding	Least pursued technology	Least pursued technology
High-Temperature Gas Reactor (HTGR)	Under development	High temperature improves efficiencies for synthetic fuel production	High temperature improves efficiencies for synthetic fuel production	High efficiency but high pressure and low power density	High efficiency but high pressure and low power density
Fluoride High-Temperature Reactor (FHR)	Under development	High temperatures and thermal delivery	High temperatures and thermal delivery	High temperature and Low pressure	High temperature and Low pressure
Molten Salt Reactor (MSR)	Under development	High temperature and thermal delivery	High temperature and thermal delivery	High temperature and Low pressure	High temperature and Low pressure
Heat Pipe Reactor (HPR)	Under development	Limited output as single unit, potential to scale	Limited output as single unit, potential to scale	High temperature and Low pressure	High temperature and Low pressure

- 출처 : INL (2023.9), Configurations of Commercial Advanced Nuclear-Maritime Applications

원자력 해양 이용

해양 적용을 위한 원자로의 조건 (CorePower, WNTI)

- ✓ 핵연료 주기
- ✓ 모듈화를 통한 다수호기 공급
- ✓ EPZ (해양 제품 범위 내 한정)



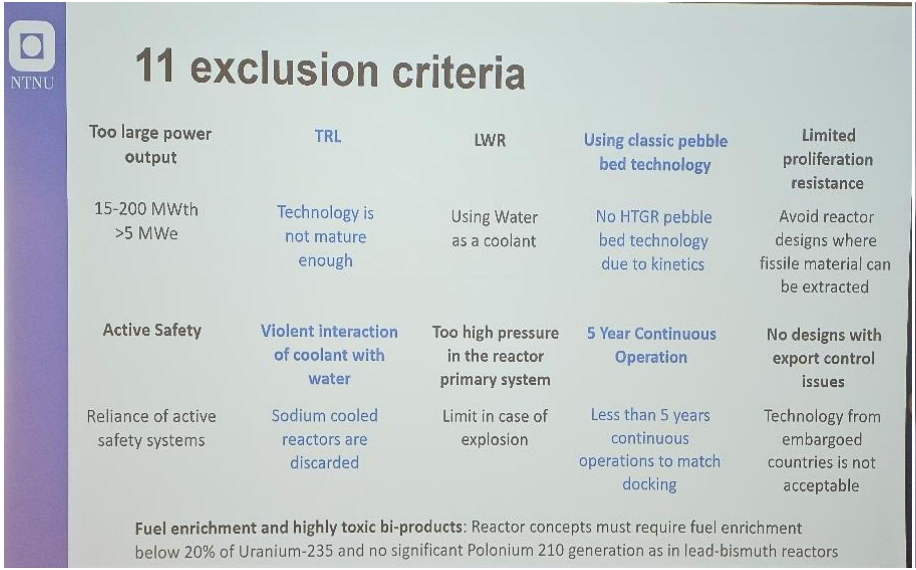
- 출처 : INL (2023.9), *Configurations of Commercial Advanced Nuclear-Maritime Applications*

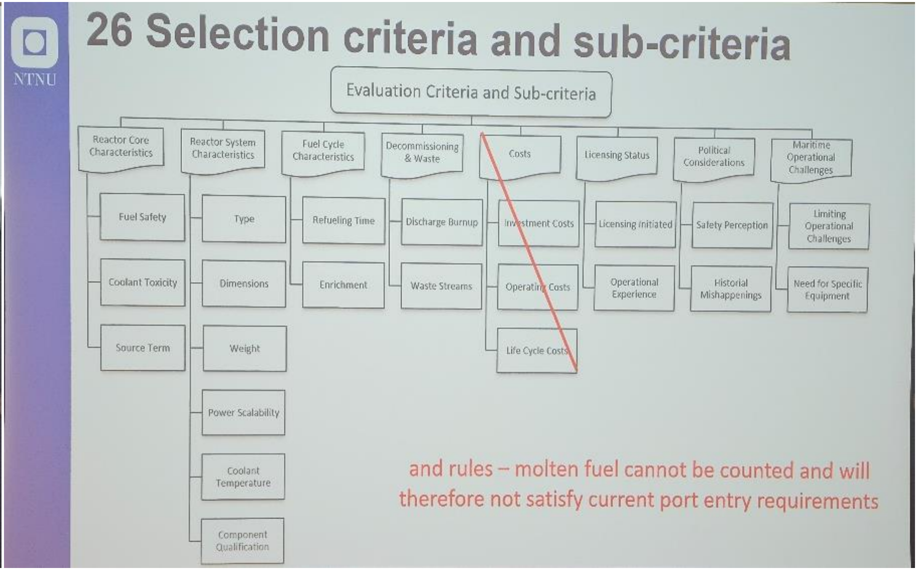
원자력 해양 이용

▪ 원자력추진선 탑재 원자로 선정 평가 (NuProShip 프로젝트)

✓ 원자로의 노형 선정 기준 및 세부 기준 항목 제시

- 고압 조건, 5년 이상의 핵연료 주기 등을 언급





부유식 해양 원전 비즈니스

IAEA 부유식 해양 원전 심포지엄 (‘23.11월)

- ✓ International Symposium on the Deployment of Floating Nuclear Power Plants – Benefits and Challenges
- ✓ 부유식 해양 원전의 건설(Deployment)에 대한 여러 고려 사항에 대한 검토 (원자력추진선은 제외)
- ✓ Small Modular Reactors for Marine-based Nuclear Power Plant (‘23.11월)

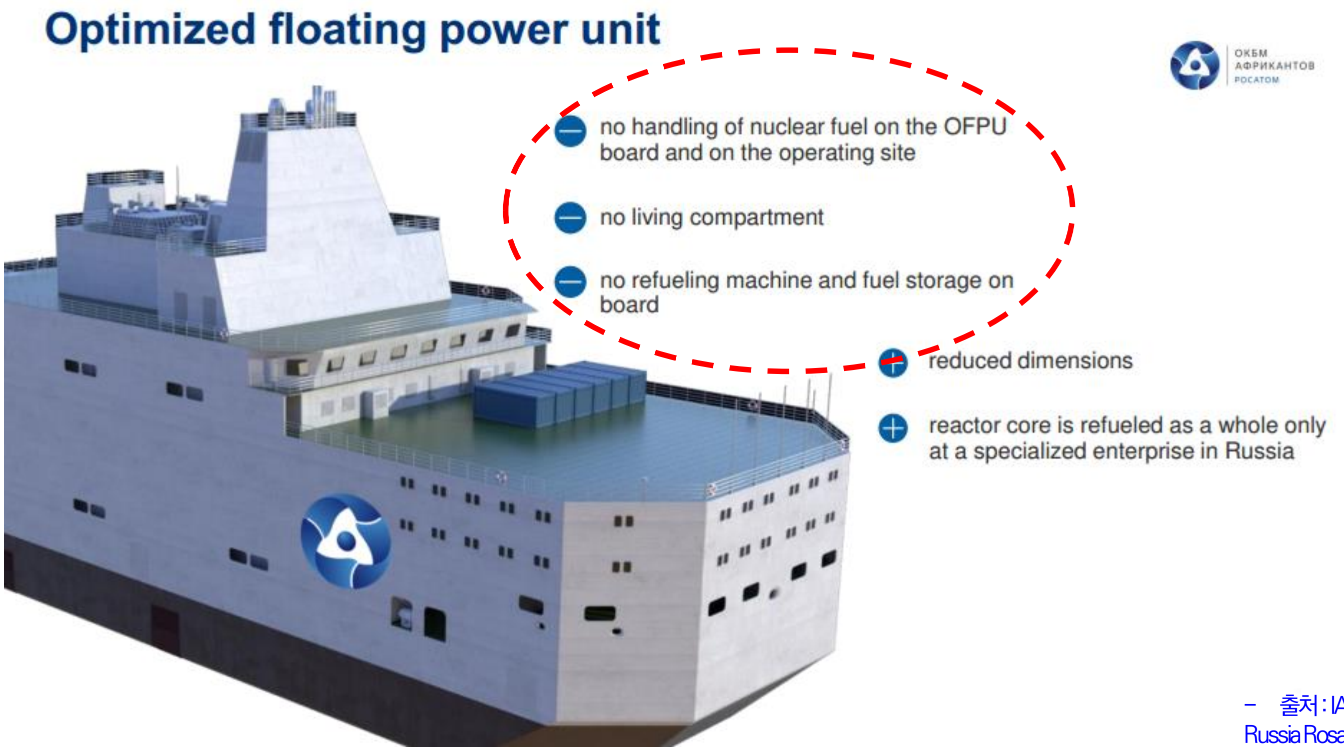
Marine-based SMR Designs

POWER RANGE OF MARINE-BASED SMR DESIGNS

해양 SMR 제품의 조건

부유식 해양 원전의 설계 요건

- ✓ Compact Design

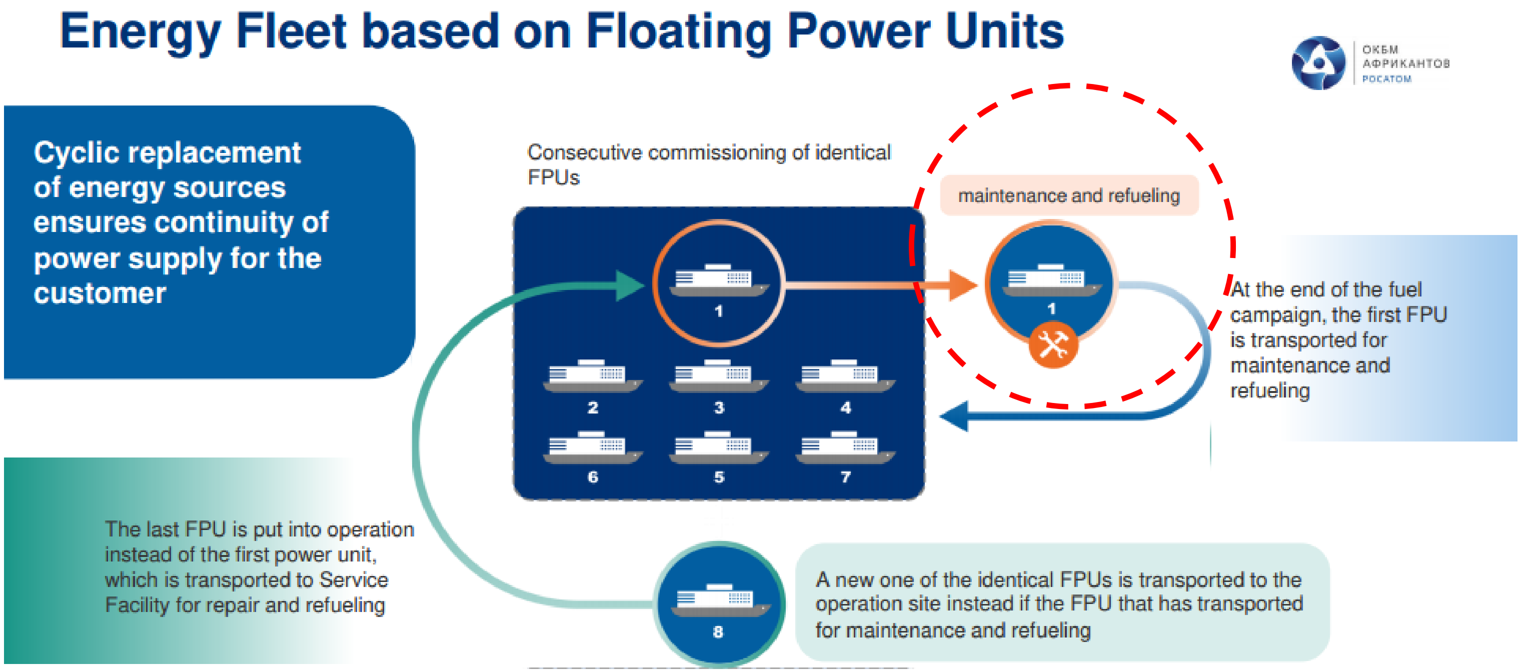


– 출처 : IAEA 부유식 원전 심포지엄 Russia Rosatom

해양 SMR 제품의 조건

▪ 부유식 해양 원전의 비즈니스 모델 제시

✓ 러시아 부유식 해양 원전 선대(Fleet) 구성



– 출처 : IAEA 부유식 원전 심포지엄 Russia Rosatom

해양 SMR 제품의 조건

부유식 해양 원전의 비즈니스 모델 제시

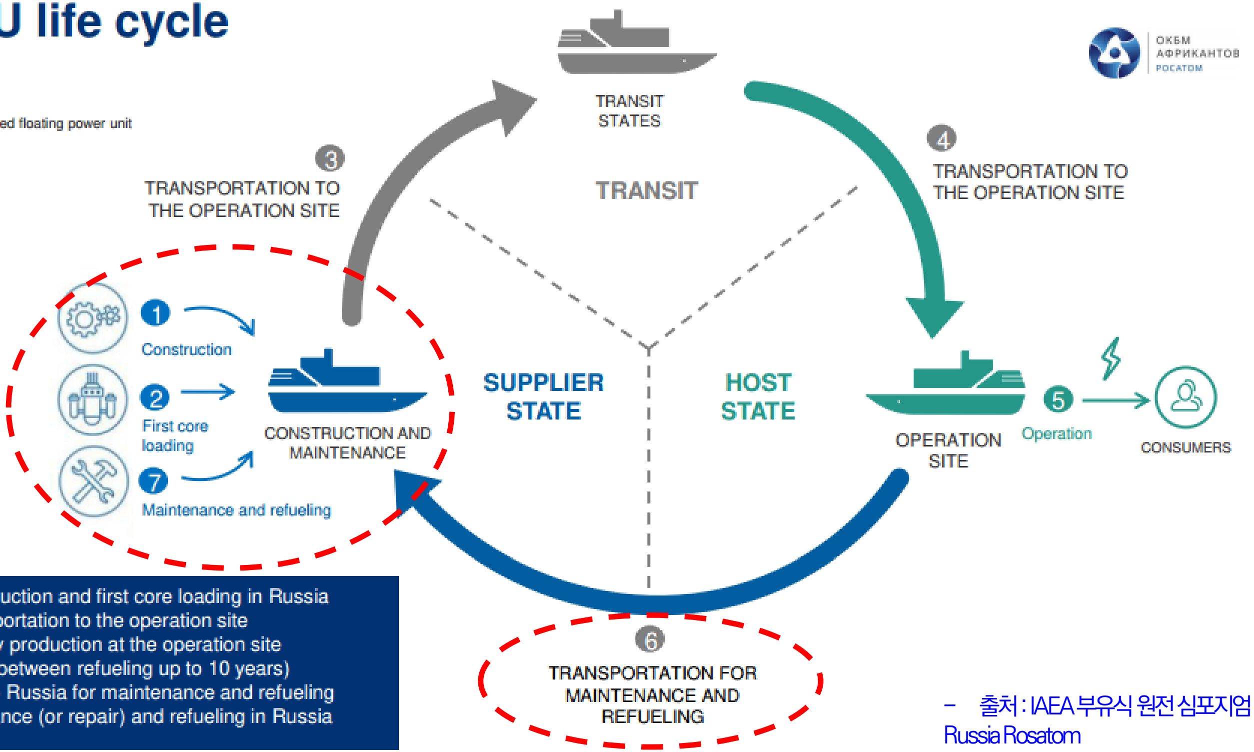
✓ 러시아 부유식 해양 원전 선대(Fleet) 구성

OFPU life cycle

* OFPU – optimized floating power unit

- the reactor is shut down;
- the heat removal systems are in a standby mode;
- the reactor parameters are monitored by the APCS** and operators.

- The safety of the FPU at all stages of the lifecycle, including transportation, is confirmed by the SAR*
- The main purpose of safety concept is to protect personnel, public and environment from the radiation impact during normal operation as well as during design- and beyond design-basis accidents



1, 2 – Construction and first core loading in Russia
3, 4 – Transportation to the operation site
5 – Electricity production at the operation site (time period between refueling up to 10 years)
6 – Return to Russia for maintenance and refueling
7 – Maintenance (or repair) and refueling in Russia

– 출처 : IAEA 부유식 원전 심포지엄 Russia Rosatom

Akademik Lomonosov 핵연료 교체

- ✓ 해양 원전 핵연료 교체 진행 (핵연료주기 : 3.5년)

Floating nuclear power plant set for first refuelling

13 October 2023

Share

Nuclear fuel has been delivered to Russia's floating nuclear power plant *Akademik Lomonosov* with the landmark refuelling set to begin before the end of the year.

First refuelling at floating nuclear power plant

24 November 2023

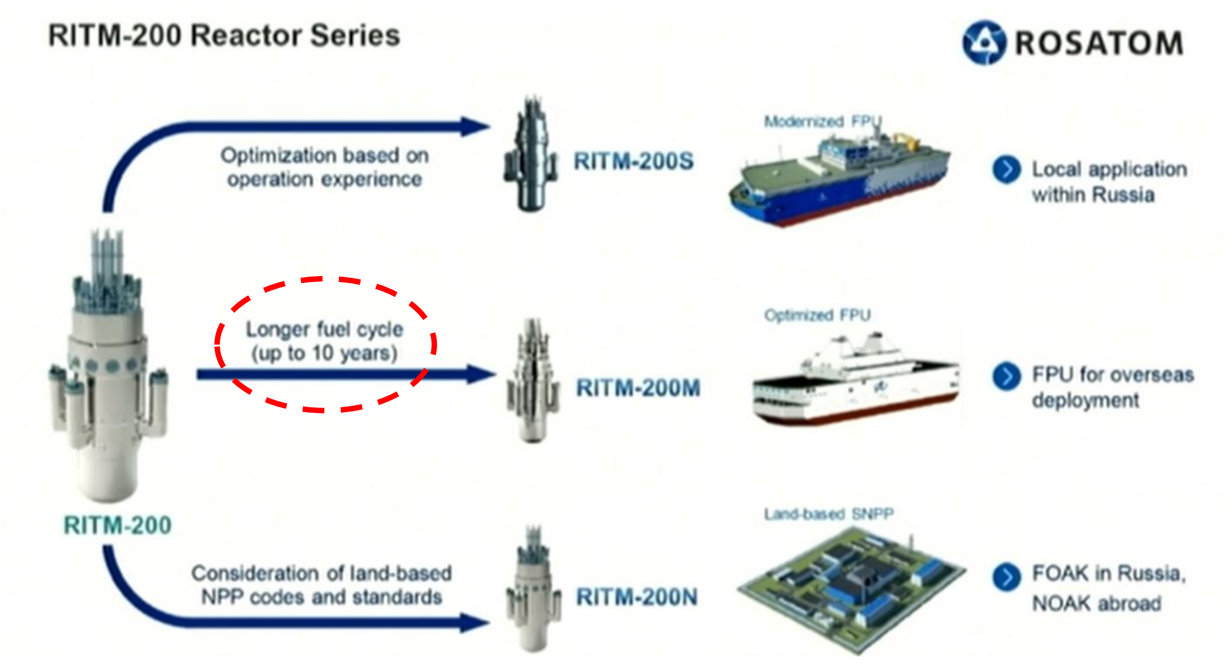
Share

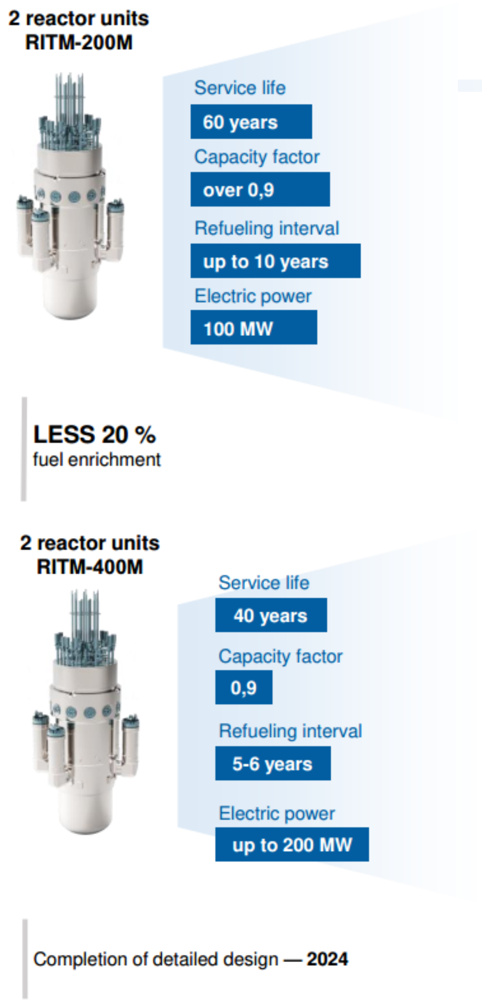
Fresh nuclear fuel has been loaded into the starboard side reactor on the *Akademik Lomonosov* in the first operation of its kind, with the process due to be completed by the end of the year, Rosatom says.

해양 SMR 제품의 조건

러시아 부유식 해양용 원자로

- ✓ RITM-200 series, RITM-400 개발 진행





해양 원자력 동향 (Rule & Regulation)

- **원자력선 규제 : SOLAS 8장 (Chap. 8 Nuclear Ships) (1974)**
  - Safety of Life at Sea
  - ✓ 원자력을 동력으로 사용하는 선박에 적용하는 12개의 규칙 명기

- **원자력선 안전 코드 : The Code of Safety for Nuclear Merchant Ships (Res. A. 491) (1981)**
  - ✓ SOLAS 8장 보강을 위한 설계(Design), 운영(Control), 검사(Survey) 등의 세부 요건 제시
  - ✓ 1960년대 연구용·실험용 목적의 원자력선 등장 시의 경수로(PWR) 기반의 기술에 대한 요건 서술

Title	SOLAS 1974 Convention / Chapter VIII (Reg.1~12) / Reg. 1
Effective Date	5/25/1980

CHAPTER VIII

NUCLEAR SHIPS

Regulation 1

Application

This Chapter applies to all nuclear ships except ships of war.

Title	SOLAS 1974 Convention / Chapter VIII (Reg.1~12) / Reg. 2
Effective Date	5/25/1980

Regulation 2

Application of other Chapters

The Regulations contained in the other Chapters of the present Convention apply to nuclear ships except as modified by this Chapter.*

* Refer to the Code of Safety for Nuclear Merchant Ships(resolution A.491(XII)) which supplements the requirements of this chapter.

Title	SOLAS 1974 Convention / Chapter VIII (Reg.1~12) / Reg. 3
Effective Date	5/25/1980

Regulation 3

Exemptions

A nuclear ship shall not, in any circumstances, be exempted from compliance with any Regulations of this Convention.

Title	SOLAS 1974 Convention / Chapter VIII (Reg.1~12) / Reg. 4
Effective Date	5/25/1980

Regulation 4

Approval of Reactor Installation

The design, construction and standards of in inspection and assembly of the reactor installation shall be subject to the approval and satisfaction of the Administration and shall take account of the limitations which will be imposed on surveys by the presence of radiation.

INTERNATIONAL MARITIME ORGANIZATION

IMO

Distr. GENERAL
A XII/Res.491
18 June 1982
Original: ENGLISH

ASSEMBLY - 12th session
Agenda item 10(b)

RESOLUTION A.491(XII)
adopted on 19 November 1981

CODE OF SAFETY FOR NUCLEAR MERCHANT SHIPS

A

THE ASSEMBLY,

RECALLING Article 16(i) of the Convention on the Inter-Governmental Maritime Consultative Organization,

RECALLING FURTHER section 7 of the Appendix to resolution 1 of the International Conference on Safety of Life at Sea, 1974, recommending the revision of the relevant provisions of the Convention in respect of nuclear ships,

NOTING the progress in nuclear engineering, the experience gained by a number of countries in operating ships with nuclear propulsion and the expected increase in the use of nuclear propulsion of merchant ships,

RECOGNIZING that the safety criteria for nuclear merchant ships differ substantially from those for conventional ships,

RECOGNIZING FURTHER that the Recommendations applicable to nuclear ships set out in Attachment 3 to the Final Act of the International Conference on Safety of Life at Sea, 1974, provide insufficient guidance for the safety criteria for such ships,

HAVING CONSIDERED the recommendation made by the Maritime Safety Committee at its forty-fourth session,

1. ADOPTS the Code of Safety for Nuclear Merchant Ships (Nuclear Ships Code), the text of which is set out in the Annex to the present resolution, which supersedes the text of the Recommendations applicable to nuclear ships set out in Attachment 3 to the Final Act of the International Conference on Safety of Life at Sea, 1974, and which provides an agreed international safety guide for the design, construction, commissioning, operation and decommissioning of nuclear powered merchant ships;

2. INVITES all Governments concerned:

(a) To take appropriate steps to give effect to the Code;

(b) To apply the Code as a supplement to the requirements of Chapter VIII of the International Convention for the Safety of Life at Sea, 1974;

(c) To inform IMCO of measures taken in this respect.

– 출처 : IMO, KR 해양 SMR 규제 JWG 발표자료

해양 원자력 동향 (Rule & Regulation)

Aspect	MH-1A (Sturgis)	NS Savannah	NS Otto Hahn	Mutsu
Type	Floating Nuclear Power Plant	Nuclear-Powered Merchant Ship	Nuclear-Powered Cargo Vessel	Nuclear-Powered General Cargo Ship
Deployment Location	Panama Canal Zone	Various ports and routes	Various ports and routes	Various ports and routes
Primary Authority	U.S. Army Corps of Engineers	U.S. Atomic Energy Commission (AEC) and U.S. Coast Guard	German Federal Ministry for Research and Technology	Japan Atomic Energy Research Institute
Reactor Approval	U.S. Army Corps of Engineers	U.S. Atomic Enrgy Commission (AEC)	German Federal Ministry for Research and Technology	Japan Atomic Energy Research Institute
Floating Unit Approval	U.S. Army Corps of Engineers	U.S. Atomic Energy Commission (AEC) and U.S. Coast Guard	German Federal Ministry for Research and Technology	Japan Atomic Energy Research Institute
Classification Society	Not directly involved	American Bureau of Shipping (ABS)	Germanischer Lloyd (GL)	Nippon Kaiji Kyokai (ClassNK)
Operational Period	1968-1976	1962-1972	1968-1979	1974-1992
Purpose	Provide power during regional hydroelectric power shortage	Demonstrate feasibility of nuclear-powered commercial shipping	Test feasibility of nuclear power in civil maritime service	Test feasibility of nuclear power in maritime service

해양 원자력 동향 (Rule & Regulation)

Rule & Regulation 검토 및 Working Group 활동

- ✓ WNTI : 원자력추진선 관련 PWR 기술, S/T Direct 추진 기반 → Advanced Marine Reactor 기준으로의 Gap Analysis 문서 제출
  - 구체적이고 명확한 규칙과 지침을 제공 & 준수 사항 명시

  → 달성해야 할 결과나 목표를 설정하고, 달성하기 위해 사용할 방법은 규제 대상자가 선택

IMO INTERNATIONAL MARITIME ORGANIZATION — E

MARITIME SAFETY COMMITEE
108th session
Agenda item 5

MSC 108/INF.21
12 March 2024
ENGLISH ONLY
Pre-session public release: ☒

DEVELOPMENT OF A SAFETY REGULATORY FRAMEWORK TO SUPPORT THE REDUCTION OF GHG EMISSIONS FROM SHIPS USING NEW TECHNOLOGIES AND ALTERNATIVE FUELS

Gap analysis of the Code of Safety for Nuclear Merchant Ships

Submitted by World Nuclear Transport Institute (WNTI)

SUMMARY	
Executive summary:	The Code of Safety for Nuclear Merchant Ships (resolution A.491(XII), adopted on November 1981) is specific to early reactor designs and needs updating to accommodate technology developments. This document contains a comprehensive gap analysis which provides a framework for the development of a revised Nuclear Code adopting the non-prescriptive technology neutral approach used by IAEA in their safety standards.
Strategic direction, if applicable:	3
Output:	3.8
Action to be taken:	Paragraph 9
Related document:	MSC 107/20

NEW **Postulated Initiating Event (PIE)**	-	A postulated event identified in design as capable of leading to anticipated operational occurrences or accident conditions. The primary causes of postulated initiating events may be credible equipment failures and operator errors (both within and external to the facility), human induced events or natural events.
	Needs to be added in line with IAEA terminology since this will be addressed in the design and Safety Assessment.	
Reactor vessel	That envelope of the nuclear steam supply system, up to and including the second isolation valve. that contains or may contain primary coolant at reactor power operating temperature and pressures.	The vessel that contains the reactor fuel and the primary coolant. The type of the vessel depends on the type of the reactor, fuel and coolant. This includes reactors that are water cooled, gas cooled and liquid metal cooled and are at high pressure or atmospheric pressure.
	Needs to be replaced since it is not technology neutral.	

해양 원자력 동향 (Rule & Regulation)

Rule & Regulation 검토 및 Working Group 활동

✓ NEMO : 부유식 원자력발전소의 배치, 운영 및 해체를 위한 적절한 표준과 규칙 개발에서 원자력 및 해상 규제 기관 지원

- 국내 : HD한국조선해양, 제일파트너스, 한국선급
- 해외 : Terrapower, Westinghouse 및 LR, BV, RINA, ABS 선급 + DNV 선급 등

NEMO NUCLEAR ENERGY MARITIME ORGANIZATION

〈NEMO〉

HD현대, '해상 원자력 에너지 협의기구' 공동 설립

▶ HD현대, 세계 민간분야 첫 해상 원자력 에너지기구 발족 주도, 해상 원자력 시장 '퍼스트무버'로 발돋움

▶ 테라파워, 웨스팅하우스 등 글로벌 원자력 선도기업과 기관 참여

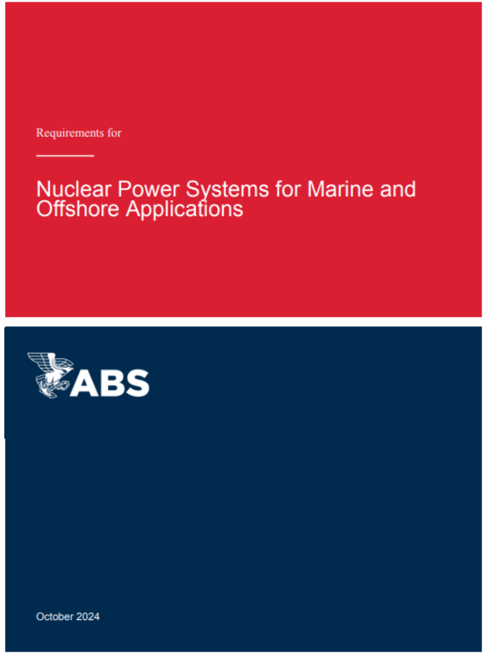
▶ 해상 원자력 분야 글로벌 표준과 규정 마련 및 상용화 추진 예정

▶ "NEMO 설립 통해 해상 원자력 분야 세계 시장 주도해 나갈 것"

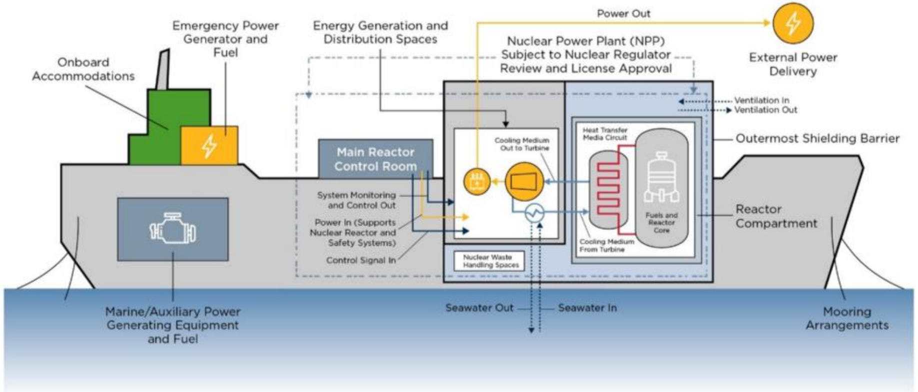
해양 원자력 동향 (Rule & Regulation)

Rule & Regulation 검토 및 Working Group 활동

- ✓ ABS : REQUIREMENTS FOR NUCLEAR POWER SYSTEMS FOR MARINE AND OFFSHORE APPLICATIONS 발간 (‘24.10月)



Simplified Example Arrangement of Nuclear Power Service Vessel



2 Reactor

The NPP is not to be used for propulsion, positioning, or maneuvering of the vessel.

Nuclear reactors are to be licensed by a recognized authority as approved by the Flag Administration. The design, testing, construction, inspection, and maintenance of the NPP, including the core, containment, cooling circuits and supplies, controls systems, safety equipment and quality assurance program are to be approved and certified by a recognized organization as approved by the Flag Administration provided they are designed such that they will function properly under the environmental conditions specified by the Owner.

– 출처 : ABS Rules

맺음말

▪ 수냉각형 원자로 해양적용을 위한 길

✓ 기술적 측면

- 한정된 선박/부유체 공간에 탑재하기 Compact Design
- 육상용과는 다른 핵연료 교체 및 사용후핵연료 저장 방법
- 핵연료 주기 (핵연료 농축도?)
- **검증된 육상용 경수로 기술적 성숙도 및 인허가 대응 경험을 활용**하는 것이 중요

✓ 제도적 측면

- IMO 원자력선 규정 Gap analysis 대응 (일체형 또는 반일체형 원자로)
- RMRS Nuclear Vessel 관련 규정 확인 (Akademik Lomonosov)
- ABS 선급 등의 해양 원자력 제품의 Rule & Regulation 대응