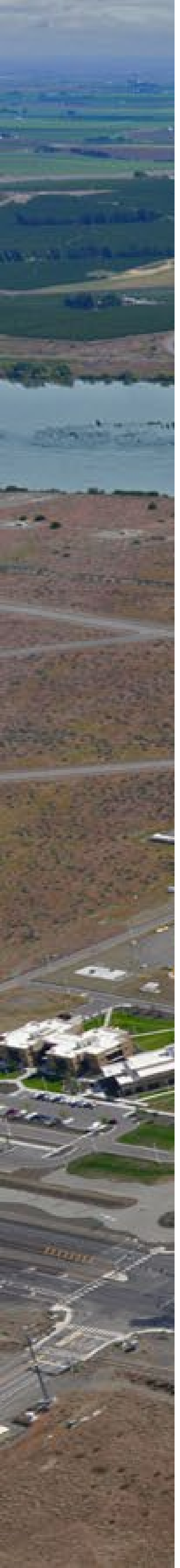

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Maritime Transport of Microreactors

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Pacific Northwest National Laboratory

Southern States Energy Board
Joint Meeting of the Radioactive Materials Transportation Committee and the Transuranic Waste Transportation Working Group

Orlando, Florida
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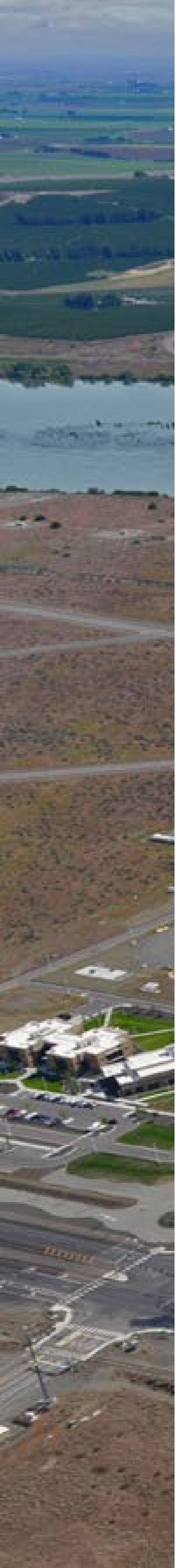

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Maritime Transport of Microreactors Topics

- What are microreactors?
- Why is maritime transport needed?
- What is the INF Code?
- What are INF Code requirements?
- Classes of INF ships
- Risk-informed maritime transport

What Are Microreactors?

- Microreactors are a class of very small modular reactors targeted for non-conventional nuclear markets
  - Also known as transportable nuclear power plants or TNPPs
- There are a variety of microreactor/advanced reactor designs, including gas, liquid-metal, molten-salt, and heat-pipe-cooled concepts
- Potential microreactor applications are:
  - Remote communities
  - Mining sites
  - Remote defense bases
  - Applications such as back-up generation for power plants
  - Humanitarian aid and disaster relief missions

Semi-Tractor and Trailer Carrying Reactor Module

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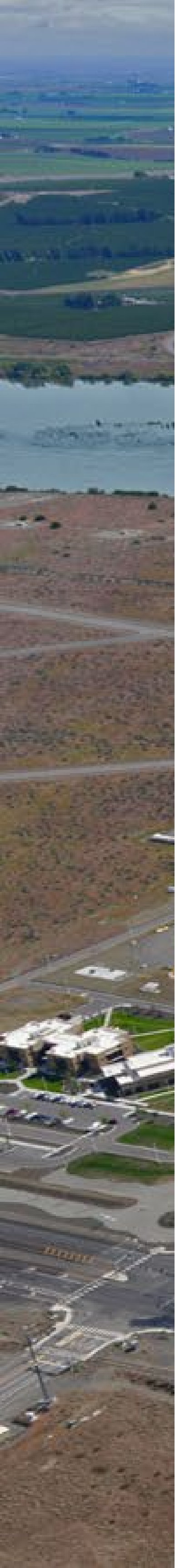
Key Attributes of Microreactors

- Microreactors have key features enabled by their small size that distinguish them from other reactor types mainly large reactors (LWRs) and small modular reactors (SMRs).
- These are:
  - Typically produce less than 20 MW thermal
    - ✓ Smaller size needed to remain transportable/deployable
  - Smaller footprint
  - Factory fabrication
  - Transportable
  - Self-regulating (enabling remote and semi-autonomous microreactor operation)
  - Rapid deployability and availability during emergency response
  - Possible operation up to 10 years or more



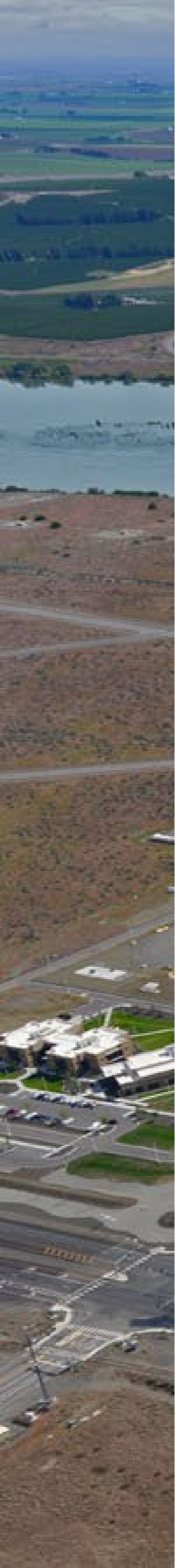
Commercial Microreactor Developers and Types

Developer	Name	Type	Power Output (MWe/MWth)	Fuel	Coolant	Moderator	Refueling Interval
Aalo Atomics	Aalo One	STR	7 MWe/20MWth	U-Zr-H	Sodium	H	3-5 years
Alpha Tech Research Corp	ARC Nuclear Generator	MSR	12 MWe/30 MWth	LEU	Flouride salt		intermittent
Antares Industries	R1	Sodium Heat Pipe	1.2 MWth	TRISO	Sodium	Graphite	
BWXT	BANR	HTGR	17 MWe/50 MWth	TRISO	Helium	Graphite	5 years
Deep Fission	DB-PWR	PWR	1-15 MWE	LEU	Water	Water	4-6 years
General Atomics	GA Micro	HTGR	1-10 MWe		Gas		
HolosGen	HolosQuad	HTGR	13 MWe	TRISO	Helium/CO2		10 years
Micro Nuclear, LLC	Micro Scale Nuclear Battery	MSR/Heat Pipe	10 MWe	UF4	FLiBe	YH	10 years
Nano Nuclear	Zeus/Odin	HTGR/MSR	1.0 MWe/2.5 MWth	UO2	Helium		
NuCube	Nu3	Heat Pipe	1 MWe/3 MWth	TRISO	Sodium	Graphite	10+ years
NuGen, LLC	NuGen Engine	HTGR	2-4 MWe	TRISO	Helium		
NuScale Power	NuScale Microreactor	LMTM/Heat Pipe	<10 MWe	Metallic	Liquid Metal	Liquid Metal	10 years
Oklo	Aurora	SFR	15 MWe	Metallic (U-Zr)	Sodium		10+ years
Radiant Nuclear	Kaleidos Battery	HTGR	1.2 MWe	TRISO	Helium	Graphite	4-6 years
Ultra Safe Nuclear	Micro Modular Reactor	HTGR	5 MWe/15 MWth	TRISO	Helium	Graphite	20 years
Westinghouse	eVINCI	Sodium Heat pipe	5 MWe/15 MWth	TRISO	Sodium	Graphite	8 years
X-Energy	XENITH	HTGR	5 MWe/10 MWth	TRISO	Helium	Graphite	3+ years

Why Is Maritime Transport Necessary?

- Many deployment scenarios for microreactors involve transport to locations outside the continental U.S.
  - Deployment outside of the continental U.S. of an unirradiated microreactor could be by air or ship
  - Redeployment or return back to the U.S. would require transport by ship
    - ✓ Radiation dose rates and shielding weights
    - ✓ Pu air transport regulations
  - This would be the case for civilian or military microreactors
- For these scenarios, the microreactor is considered cargo and does not provide propulsion or is a component of a floating nuclear power plant (FNPP)

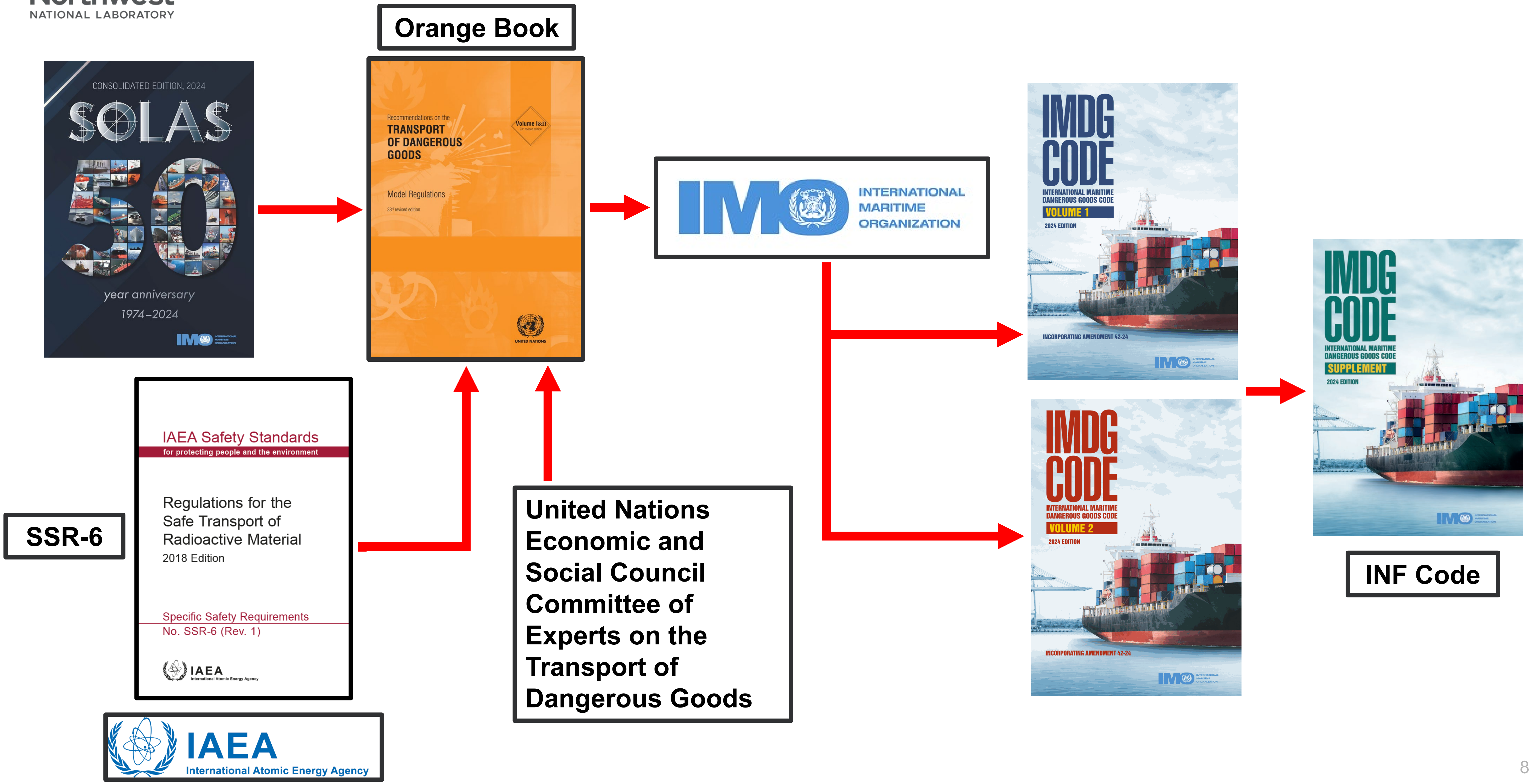
Photo courtesy of World Nuclear Transport Institute (WNTI)



What Is The INF Code?

- The Safety of Life at Sea (SOLAS) convention is one of the most important international agreements regarding merchant ship safety
  - Mandates standards for vessel construction, equipment, and operation, focusing on lifesaving appliances, fire prevention, and emergency preparedness
  - Chapter VII of SOLAS requires compliance with the International Maritime Dangerous Goods (IMDG) Code
- International Maritime Organization (IMO) is the global standard-setting authority for the safety, security and environmental performance of international shipping
  - IMO an agency of the United Nations
- International Maritime Dangerous Goods (IMDG) Code was developed by the IMO as an international code for the maritime transport of dangerous goods
  - IMDG Code lays out the regulatory framework for all aspects of handling dangerous goods and marine pollutants in sea transport
  - IMDG Code is harmonized with IAEA Specific Safety Requirements No. SSR-6, Regulations for the Safe Transport of Radioactive Material
- INF Code – International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Waste on Board Ships
  - The INF Code is contained in a supplement to the IMDG Code
  - INF Code was introduced in 1993 and became mandatory in January 2001

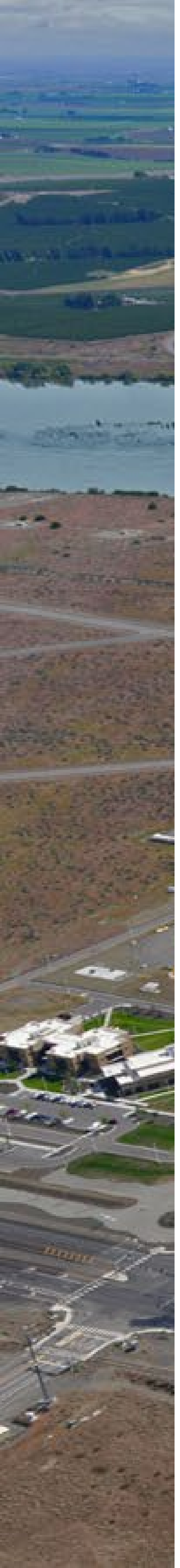
Document Relationships



INF Code Requirements

- INF Code establishes three classes of ships
- Based on current projected transportable microreactor core radionuclide inventory calculations, a Class INF 2 or INF 3 ship would likely be required to transport a microreactor containing irradiated fuel
- IAEA Specific Safety Requirements No. SSR-6, *Regulations for the Safe Transport of Radioactive Material*, also applies
- Other conventions also would apply, such as the International Convention for the Prevention of Pollution from Ships (MARPOL) protects the marine environment from pollution by vessels

Class of INF Ship	Criteria
INF 1	Ships that are certified to carry materials that have an aggregate radioactivity of less than 4,000 TBq (1.1×10^5 Ci).
INF 2	Ships that are certified to carry irradiated nuclear fuel or high-level radioactive wastes that have an aggregate radioactivity less than 2×10^6 TBq (5.4×10^7 Ci) and ships that are certified to carry plutonium that has an aggregate radioactivity less than 2×10^5 TBq (5.4×10^6 Ci).
INF 3	Ships that are certified to carry irradiated nuclear fuel or high-level radioactive wastes, and ships that are certified to carry plutonium that has no restriction on the aggregate radioactivity of the materials.



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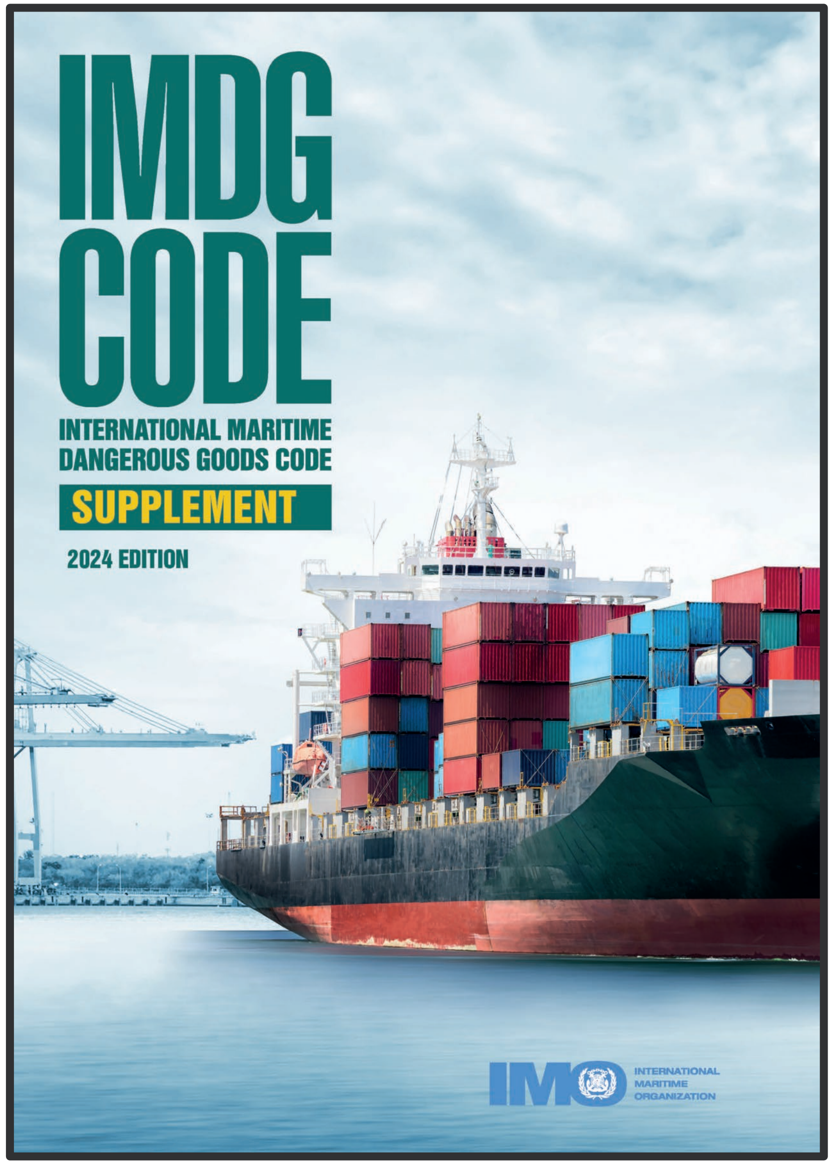
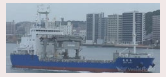
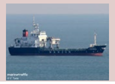
INF Code Requirements

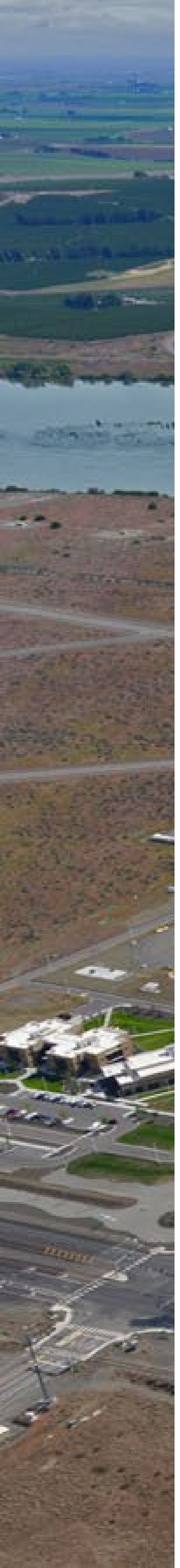
- Damage stability
- Fire safety measures
- Temperature control of cargo spaces
- Structural considerations
- Cargo securing arrangements
- Electrical power supplies
- Radiological protection
- Management and training
- Shipboard emergency plan
- Notification in the event of an accident involving INF cargo
- It is possible to refit existing ships to meet INF 1 or INF 2 requirements, but an INF 3 ship will likely need to be purpose-built
  - The MCL Trader was refit in 2009 to meet INF 2 requirements for the Russian Research Reactor Fuel Return (RRRFR) Program

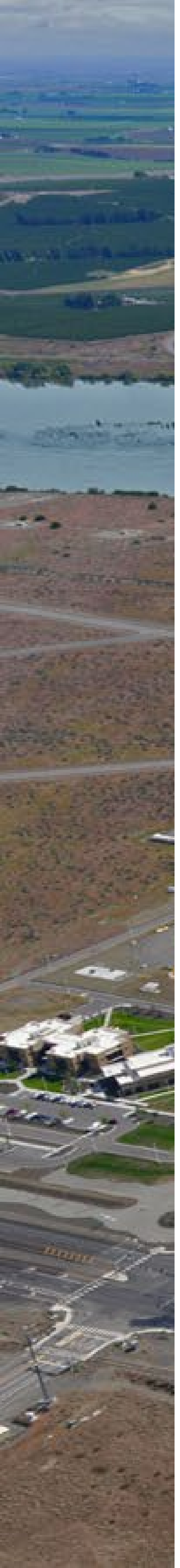


Worldwide INF 3 Ships Currently in Service

Vessel			IMO No.	Built	Gross Tonnage	Deadweight Tonnage (MT)	Length (m)	Beam (Width) (m)
		Xin An Ji Xiang	9928530	2020	5656	1931	96	18
		Seiei Maru	9810848	2019	4568	3206	100	16
		Sigrid	9631840	2013	6694	1600	100	19
		Rossita	9531894	2011	2557	1620	84	14
		Pacific Egret	9464871	2010	6776	4408	104	17
		Pacific Grebe	9464883	2010	6840	4902	104	17
		HJ Cheongjeongnuri	9488449	2009	2959	1221	79	16
		Pacific Heron	9372913	2008	6776	4916	104	17
		Kaiei Maru	9364095	2006	4924	2795	100	16
		Rokuei Maru	9137935	1996	4913	2810	100	16
		Tien Kuang No. 1	9015917	1991	834	738	53	11
		Imandra	8953409	1980	5806	2186	130	17
		Serebryanka	8929513	1974	2925	1625	102	15

Gross tonnage is a measure of a ship's overall internal volume. Gross tonnage is dimensionless.
Deadweight tonnage (DWT) is a measure of how much weight a ship can carry, so it includes the sum of the weights of cargo, fuel, fresh water, ballast water, provisions, passengers, and crew. This measurement does not include the empty weight of the ship, which means that DWT represents the difference between the number of tons of water a vessel displaces "light" and the number of metric tons it displaces when submerged to the "load line." DWT is measured in units of metric tons.





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Military Sealift Command Large, Medium-Speed, Roll-on/Roll-off (LMSR) Ships

- For comparison, Military Sealift Command LMSR ships have the following characteristics:
  - Bob Hope and Watson Classes: 290 m long with a beam of 32 m
  - Gordon Class: 291 m long with a beam of 32 m
  - Shugart Class: 277 m long with a beam of 32 m

USNS Bob Hope

USNS Watson

USNS Gordon

USNS Shugart

Key Safety Features of Class INF 3 Ships

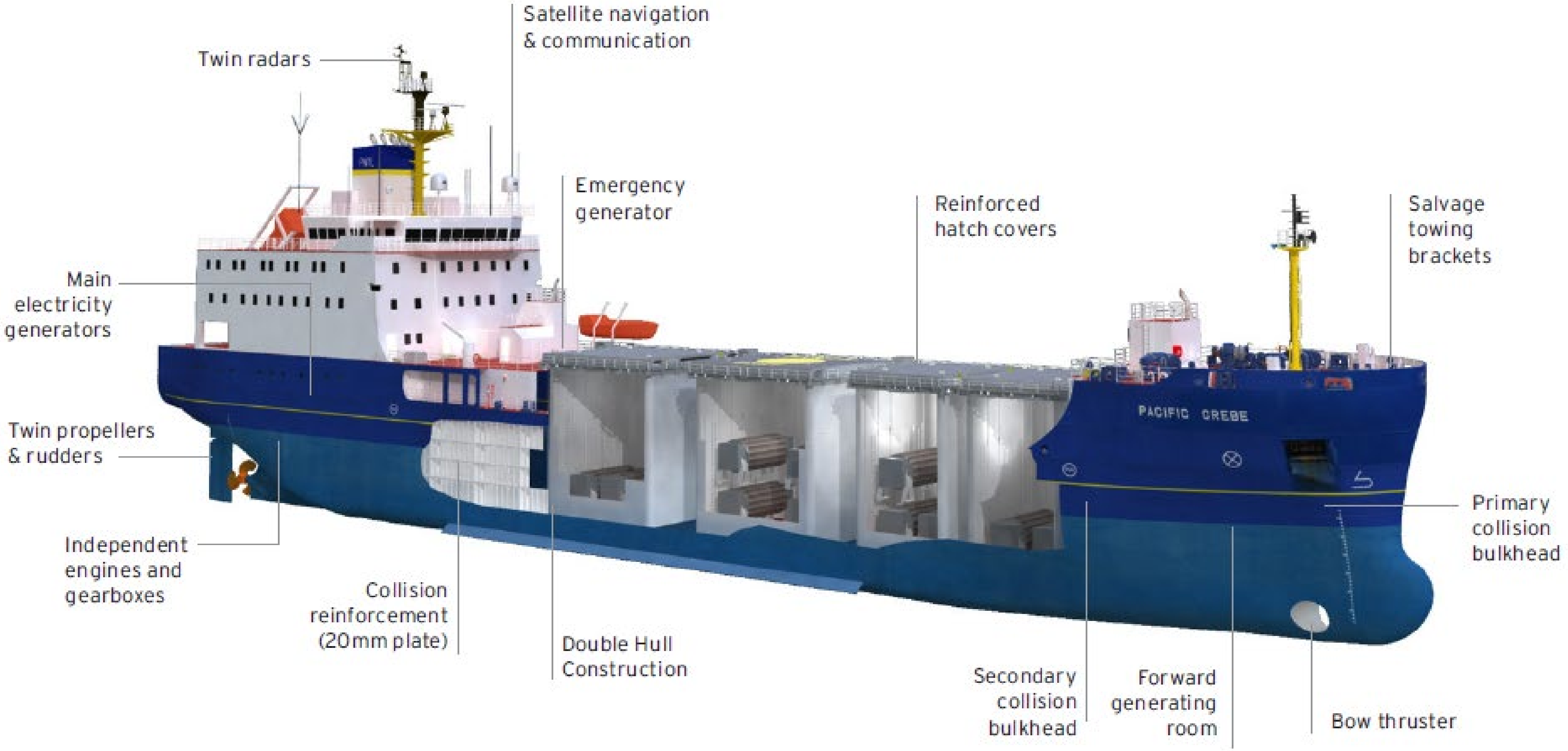
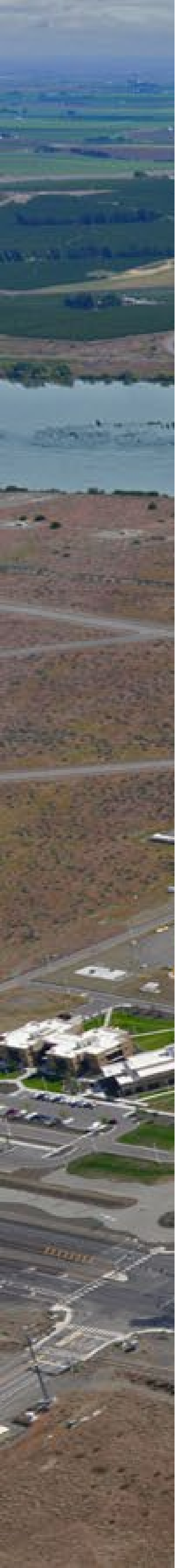


Image courtesy of PNTL

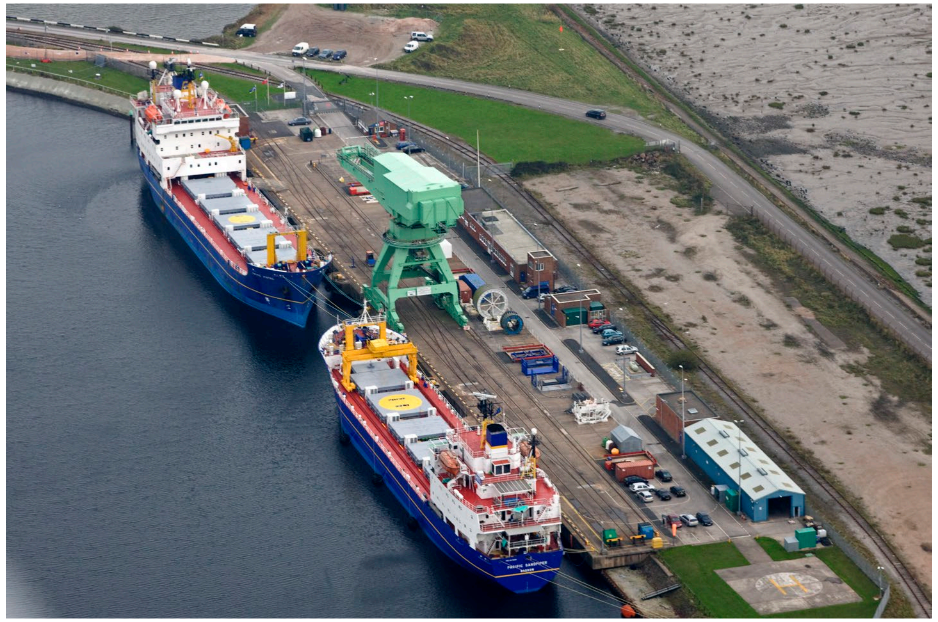


INF 3 Ships Are Available for Commercial Hire

- There are three Class INF 3 ships available for commercial hire from Pacific Nuclear Transport Limited (PNTL)
  - Pacific Egret, Pacific Grebe, and Pacific Heron
  - The PNTL ships are United Kingdom (UK) flagged; there are no United States-flagged Class INF 3 ships

Length	104 meters
Beam (Width)	17 meters
Draft	6.75 meters
Number of Holds	4
Capacity	20 transportation casks
Design Speed	14 knots
Deadweight Tonnage	4,408 metric tons (Pacific Egret), 4,902 metric tons (Pacific Grebe), 4,916 metric tons (Pacific Heron)
Gross Tonnage	6,776 (Pacific Egret and Pacific Heron), 6,840 Pacific Grebe
Engine	2 diesel engines, each with 3,600 hp
Principle Cargo Carried	Mixed Oxide Fuel Assemblies (Pacific Egret and Pacific Heron) High-Level Waste and Compacted Waste (Pacific Grebe)

Pacific Heron, Grebe, and Egret, and Port of Barrow



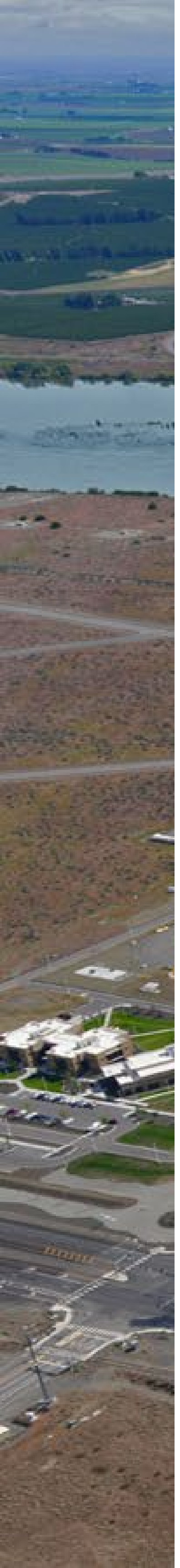
Images courtesy of PNTL and PNNL

SIGRID – Sweden's INF-3 Ship

- Built in Galati, Romania by Damen Shipyard
- Launched in October 2012, first shipment in January 2014
- Roll-On/Roll-Off and Lift-On/Lift-Off
- Double hull, redundant systems
- Operates in Baltic Sea – has ice breaking capabilities including an ice breaking bow

Length	99.5 meters
Beam (Width)	18.6 meters
Design Draft	4.5 meters
Number of Holds	1
Capacity	12 transportation casks
Service Speed	12 knots
Deadweight Tonnage	1,600 metric tons
Gross Tonnage	6,694
Main Engine	4x825 kW diesel engines
Principle Cargo Carried	TN 17 transportation casks

SIGRID – Sweden's INF-3 Ship



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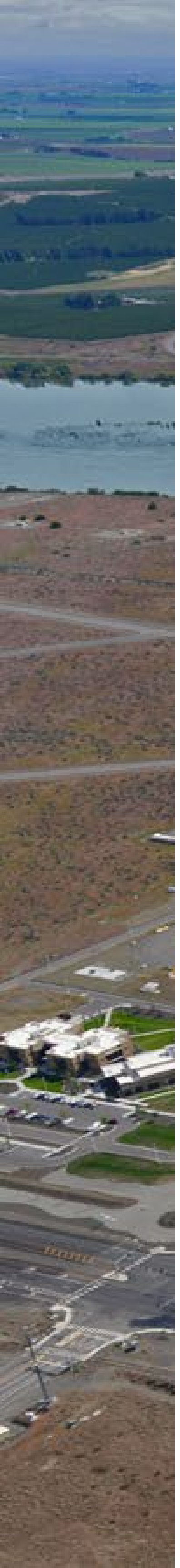
Are There Other Requirements?

- Pacific Heron, Grebe, and Egret were designed for Japanese reactor ports, this drives ship size and configuration
  - Relatively shallow draft
  - Lift-on/Lift-off versus Roll-on/Roll-off
- Japan has additional requirements (KAISA 520)[1] that mandate additional safety features in addition to what is required by the INF Code
  - Require that an INF 3 ship has a collision-resistant structure
  - In the case of the PNTL INF 3 vessels, this has resulted in several hundred metric tons of additional collision reinforcement plate being added between the inner and outer hulls
  - The purpose of this reinforcement is to reduce the risk of a colliding ship penetrating through to the hold and potentially causing damage to the packages
  - KAISA 520 also contains dose rate criteria, e.g., 1.8 uSv/h in living quarters and spaces normally occupied by persons aboard the ship
- Ships operate in pairs based on US-Japan bi-lateral agreement

1. Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT), "Regulations for Carriage and Storage of Dangerous Goods on Ship"

Other Features

- Pacific Grebe and Heron have cooling in the holds, Pacific Egret has no hold cooling
- Holds contain gamma and temperature monitoring but no neutron monitoring
  - Handheld neutron monitoring instrumentation available (Rem Ball)
- Orientation of transportation casks in holds is normally port-starboard, but adapter plates can be used to change the orientation to bow-stern
- Gamma shielding on sides of holds, gamma and shield water tank between Hold 4 and accommodation areas, gamma and neutron shielding in hatch covers
- Holds have fire suppression system for each hold (misting system). Holds can be flooded separately.
  - If a microreactor contained metallic sodium such as in heat pipes, an inert gas fire suppression system could be required



Other Features

- Lift plans are developed to not exceed 9-meter drop height specified in IAEA and NRC regulations
  - Port conditions (tides) can alter lift heights
  - Individuals typically occupy the holds during loading, holds not occupied during transport unless instrumentation failure or cooling system failure occurs
  - Time and motion studies for loading and unloading have been conducted
- Multiple exercises and training for crew, have emergency response procedures notebook
  - Redundancy in training across crew responsibilities
  - Crew trained in damage control, fire training, evacuation training, etc.
- Capable of operating 120 days at sea plus 10% buffer remaining at highest burn rate
  - This equates to fueling one time at UK port, sailing to the Japanese coast, retrieving cargo, and sailing back to the UK under rough seas conditions without refueling or stopping at additional ports
  - Fuel usage curves developed for “Eco-speed” and used as goal
  - Experimental sails under evaluation by PNTL/NTS to further reduce fuel consumption
- Ships operate on diesel exclusively (no bunker fuel)

Risk-Informed Maritime Transport

- PNNL developed a plan for establishing a licensing pathway for a transportable nuclear power plant, containing its unirradiated and irradiated fuel, as a transportation package for maritime transport using a probabilistic risk assessment framework to meet the regulatory requirements of 10 CFR Part 71
- PNNL currently executing that plan for pathway development for DoD Strategic Capabilities Office and Office of Chief Engineers, Nuclear Power Branch
- Plan will include compensatory measures to provide equivalent safety to the public, worker, and environment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PNNL-34962 Rev. 0

Plan for the Development and Application of a Risk Assessment Approach for Transportation Package Approval of a Transportable Nuclear Power Plant for Maritime Shipment

January 2024

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U.S. DEPARTMENT OF ENERGY

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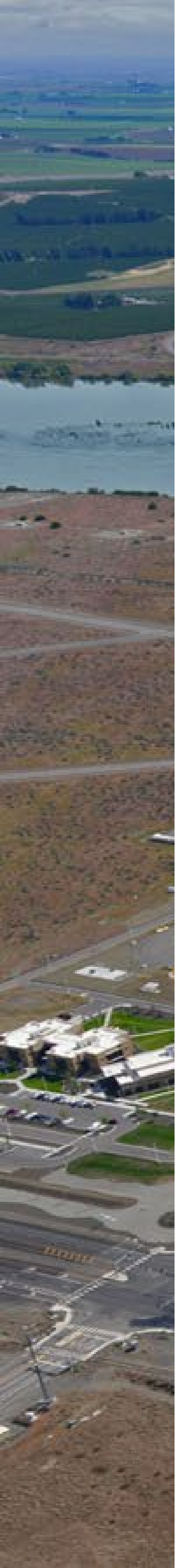

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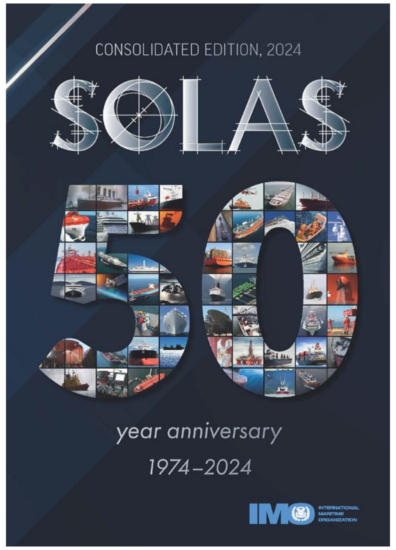

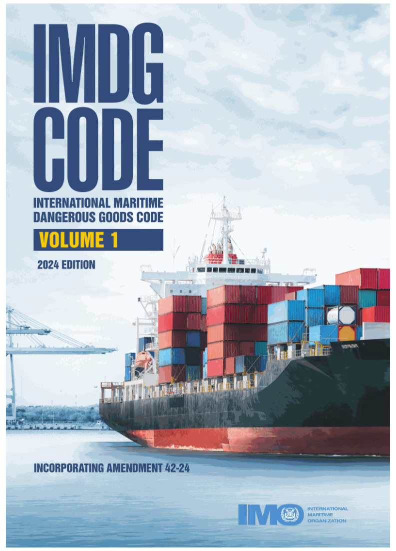

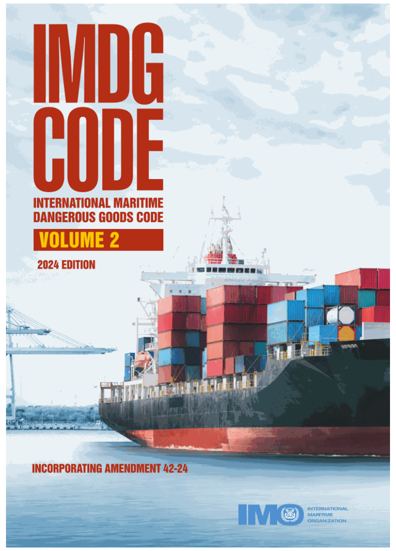

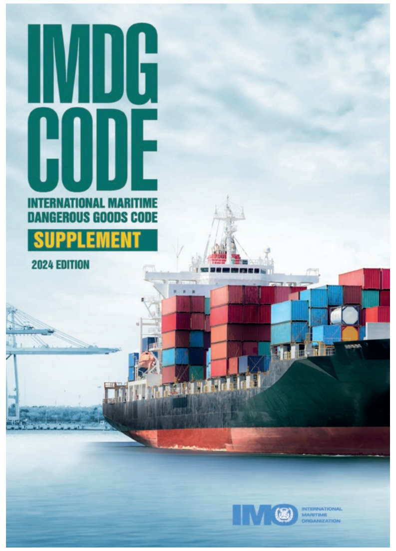

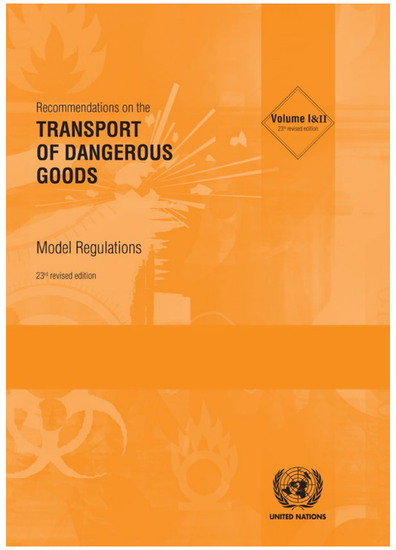

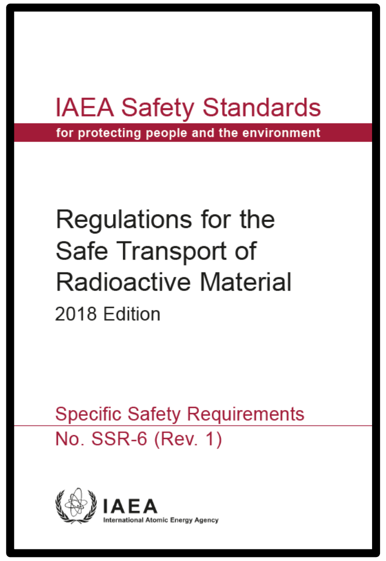

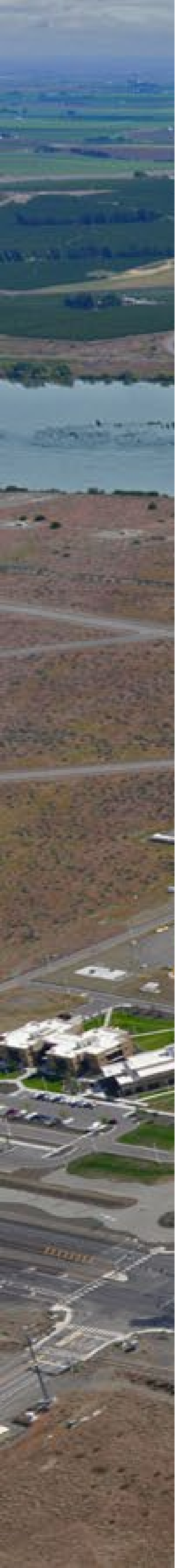

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Thank you