Maritime
Nuclear
Application
Group

Introduction to Advanced Commercial Nuclear for Maritime

September 2022

Contents

1. Introduction

1.1. The Maritime Nuclear Application Group

The Maritime Nuclear Application Group (MNAG) is a working group convened by the National Reactor Innovation Center (NRIC) at Idaho National Laboratory, the American Bureau of Shipping (ABS), and Morgan, Lewis, and Bockius LLP. MNAG is a research hub and resource center that brings together experts from the maritime and nuclear energy sectors to facilitate the demonstration of advanced nuclear technologies for a range of marine applications. MNAG fulfils this mission through strategic studies of potential maritime applications, by identifying domestic and international legal and regulatory hurdles, cataloguing and sharing of relevant information resources, and collaborating and coordinating with global stakeholders of all types. MNAG aims to support near-term field demonstrations of advanced reactor technologies in marine settings by aligning with the U.S. Department of Energy's National Reactor Innovation Center (NRIC).

MNAG's membership includes representatives of organizations and firms from:

- Advanced Nuclear: System designers, Vendors, National Laboratories, Policy non-profits, Academia
- Maritime: Vessel Owner/Operators, Classification, Maritime Law, Insurance, Flag States
- U.S. Government: Independent regulatory organizations and Executive Branch department
- Environmental: Industry groups

1.2. Scope of this Report and Overview of MNAG Report Series

With the majority of all traded goods carried at sea, the global shipping industry is at the heart of international commerce. Large diesel engines, some of the most durable and reliable power sources available, have enabled the globalization of trade. The isolation of ships at sea within challenging, dynamic marine environments requires reliable and durable powering solutions onboard.

While marine internal combustion engines are known to be durable and reliable, they may emit harmful pollutants and greenhouse gases (GHGs) unless the emissions are specifically addressed. Rising social awareness and advocation for sustainable decarbonization is driving the marine industry to reduce its emissions and achieve a true-zero emission power source which can be competitive with conventional power systems. At the same time, advanced types of nuclear reactors are under development as potential solutions for both rising global energy demands and sustainable decarbonization concerns. Therefore, the nuclear industry is searching for new mass markets where advanced technology can be deployed to demonstrate the existing environmental credentials and inherent safety of fission.

In this first of four reports, an introduction on the topic of advanced nuclear solutions for maritime applications is provided, describing the composition, dynamics and mechanics of ocean transportation so that both nuclear and maritime sectors can explore the opportunities and challenges that lie ahead for the intersection of these two industries. Key criteria for success in the maritime industry are introduced to begin understanding how advanced nuclear solutions can successfully integrate with marine applications. As a demonstrative example, and based on the information available to MNAG, the report looks specifically at the unique opportunity for advanced nuclear marine applications between the United Kingdom and the United States of America. Investigating the readiness of the regulatory frameworks, infrastructure and technologies within these two countries can provide an explanatory baseline to consider advanced nuclear solutions for other national and international maritime applications.

The second report will address the regulatory landscape and the gap between nuclear and maritime regulations that must be bridged. Current applicable rules will be introduced, and the regulatory requirements required on both nuclear and marine industries will be examined.

In the third report, advanced nuclear technologies will be described and discussed with respect to the criteria for success within maritime applications.

The fourth report will introduce the potential environmental, economic, and social justice impacts that could result from the combination of advanced nuclear solutions within the maritime sector. This includes how advanced nuclear solutions can reinvigorate the U.S. shipbuilding sector by boosting jobs and creating global leadership. There can be an opportunity for the U.S. shipbuilding sector and ship register to grow again, providing an important new hub of growth for states and Government. The report will also describe in general how port environments can be decarbonized and improved.

2. Background

2.1. Environmental Impact from Global Maritime Fleet

Ships must be independently powered and sufficiently robust to survive sea routes. At the heart of global marine industries, ship propulsion and powering systems must be reliable and durable and be appropriately efficient to remain competitive.

The Fourth GHG Study (2020) from the International Maritime Organization (IMO) estimated that total shipping emitted 1,056 million tons of CO_2 in 2018 which accounted for 2.9% of total global anthropogenic CO_2. If left unchecked, the IMO has indicated that shipping emissions could increase from 2012 levels between 50% and 250% by 2050.

Given the urgency of reducing GHGs to limit the anthropogenic effect of climate change, the International Maritime Organization (IMO) has declared the goal that current GHG emissions are to be reduced by half by 2050, and future revisions of this goal are expected to impose more stringent requirements. International shipping can address these goals by increasing fuel efficiency, switching to low-carbon alternative fuels such as liquefied natural gas (LNG, primarily composed of methane), methanol/ethanol, biofuels, ammonia, or hydrogen. Innovative power solutions can be used such as advanced energy storage systems, clean power produced from fuel cells, or renewable energy generation from solar or wind power. Emission-reducing equipment can be used such as scrubbers, exhaust gas recirculation (EGR) or carbon capture devices. However, many of these options only offer a partial solution to eliminating GHG emissions. Advanced nuclear power for marine has the potential to be a key solution to the future decarbonized alternative power problem.

To investigate the emissions from ship propulsion further, later sections in this report summarize the global fleet breakdown by major ship types, market growth, and lifecycle emissions.

2.2. Lessons from the Nuclear Navies

The U.S. and U.K. Navy nuclear propulsion programs, which have operated since the 1950s with over nine generations of pressurized water reactor (PWR) technologies, have become highly respected and specialized branches of their countries' militaries. Using specialized operating procedures, excellent safety records have led to the suggestion that commercial marine industries could adopt a new generation of advanced reactor technologies with a similar approach to marine safety and security.

However, modern naval reactors are not suited for civilian applications due to the highly enriched uranium fuel used, which would likely not be allowed in commercial applications due to national and international security and proliferation concerns.

Figure 1: Crew members line the deck of the nuclear-powered attack submarine USS NORFOLK (SSN-714) – Image courtesy of NARA & DVIDS Public Domain Archive

Low-enriched uranium-fuelled naval reactors would require much larger reactors than the highly-enriched uranium-fuelled reactors, and would require frequent refuelling, posing a major challenge in managing both the supply of fresh fuel and the handling of spent fuels. While the reactor technologies of the nuclear navies may not be suited for commercial shipping, the safety, training, and operational regimes are. This point was referenced by the U.S. Special Envoy for Climate John Kerry reflecting on his own Naval career during COP26 in Glasgow in 2021. (see: https://splash247.com/nuclear-powered-ships-make-waves-in-glasgow/)

2.3. Advanced Nuclear Technologies

Advanced nuclear technologies are emerging today as potentially viable for commercial shipping or offshore applications.

The U.S. Department of Energy is currently funding the demonstration, risk reduction, or development of ten new reactor technologies through its 'Advanced Reactor Demonstration Program' (ARDP) in collaboration with private enterprises under a public-private cost-share model.

Adapting reactor designs for applications within maritime operating environments may require adherence to a specific set of key criteria. This may result in only some designs being suitable to power commercial maritime applications.

Some novel reactor designs could find the maritime sector to be ideal to prove their value in new, scalable markets, while other novel reactor designs may be better suited to operate on land or in more controlled environments.

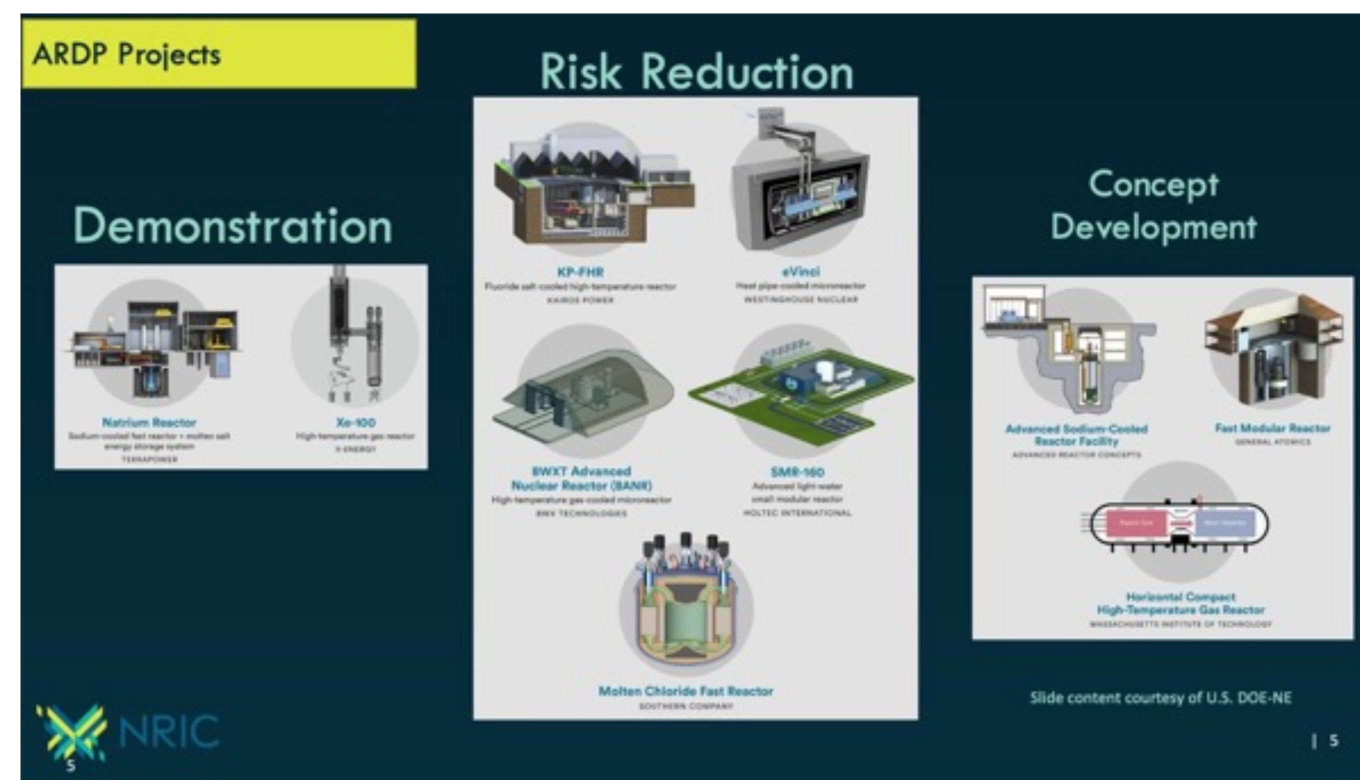


Figure 2: Reactor Development Supported by the U.S. Department of Energy ARDP (Advanced Reactor Demonstration Program)

3. The Global Fleet

This section discusses the global and U.S. fleet presenting information on the size, capacities, and emissions from ships. The information may reveal opportunities where nuclear-powered propulsion systems could be appropriate, or where the application of nuclear power could reduce emissions from shipping.

In 2020, the total global fleet reached 98,140 commercial ships of 100 gross tons and above. The fleet has a combined carrying capacity of 2.06 billion dead weight tons (dwt), sailing 59.5 billion ton-miles. The United Nations Conference on Trade and Development (UNCTAD) reported that in 2019 the volume of international maritime trade was 11.08 billion tons, representing approximately 80% of all global trade.

As shown in Table 1, of the global fleet, about 17,000 ships are large to medium-size (approximately 20%). These 17,000 ships have a combined 320 GW of installed power, consuming 265 million metric tons of heavy fuel oil per annum (p/a), and emitting almost 800 million tons of CO2 each year (approximately 80%). In effect, 20% of the global fleet emits approximately 80% of the emissions from shipping transport.

Focusing sustainable decarbonization efforts on the medium-to-large ship segment may be reasonable to make the most impact on the fewest number of vessels.

Table 1: The 2020 Global Fleet annual fuel performance and emissions

GLOBAL FLEET 2020		TANKERS	DRY CARGO	CONTAINER	CRUISE	TOTAL
Large and Medium Sized Ships		4,721	7,938	4,312	167	**17,138**
Total fleet Consumption p/a	MT	55,891,957	95,788,885	107,252,951	4,544,250	**263,278,043**
Propulsion energy required p/a	MW	66,459	116,151	123,255	11,950	**317,815**
Est. CO_2 + GHG emissions	mil. MTs p/a	167,675,872	287,366,654	321,758,852	13,632,750	**790,434,127**

Source: CORE POWER, SSY, Clarksons and IMO

3.1. Maritime as a Value Chain Component

In addition to the cost of fuelling marine assets along their routes, total vessel expenses (i.e., capital costs, CAPEX and operational costs, OPEX) include the costs of ship procurement and manufacture, operational maintenance costs, and other fees and exchanges related to taxes, charters, and trading goods. Vessel capital and operational expenses directly affect the global trade market prices and are essential in reducing prices along the value chain.

According to UNCTAD, the total sum of global trade was approximately 13.5 billion tons in 2020. That trade is carried by three main categories of ship:

- Commodities (Energy, Food, Minerals, etc.) in Bulk Carriers and Tankers
- Industrial Components, Durable Consumer Goods in Containerships
- Project Cargo, Specialist Cargo in Specialist Cargo Vessels

High level patterns in global trade shaped by regional producers and consumers show us that the largest bulk of commodity movement from West to East is in the form of raw materials and manufactured goods while commodities moving from East to West are primarily industrial components and durable consumer goods.

Asia has benefited from greater integration into the global manufacturing and trading networks, promoting intra-regional trade. Capitalizing on the fragmentation of globalized production processes, the eastern half of the Asian continent has become a maritime hub that brings together over 50% of global maritime trade volumes.

3.2. The U.S. Fleet

According to the U.S. Maritime Administration (MARAD), the combined fleet that make up the U.S. domestic market totals over 36,000 units with a cargo carrying capacity of 82 million tons.

It is estimated that approximately 6,000 of these vessels are either self-propelled or designed to power barge clusters on the waterways. See Table 2.

Table 2: U.S. domestic fleet and capacities

	Dry cargo barges	Tankers	Total nonself-propelled	Dry cargo / passenger	Ferries, railroad car	Tankers	Total self-propelled	Total
Units	27,645	5,183	32,828	2,841	571	78	3,490	36,318
Units p/Power Unit	15	10						
Est Total Power units	1,843	518	2,361	2,841	571	78	3,490	**5,851**
Cargo capacity (MTs)	48,917,025	18,253,438	67,170,463	7,018,914	4,034,215	4,034,215	15,087,344	82,257,807

(ref. Marad 2020 – https://www.maritime.dot.gov/data-reports/data-statistics/data-statistics)

The combined fleet consumes an estimated 18.5 million metric tons of fossil fuels each year with an estimated 10 million tons consumed on the coasts and lakes, and 8.5 million tons on the rivers. Total emissions from the U.S. fleet are estimated at 48.7 million tons of CO2 per year. See Table 3 and Table 4.

Table 3: U.S. domestic fleet fuel consumption

	Dry cargo barges	Tankers	Total nonself-propelled	Dry cargo / passenger	Ferries, railroad car	Tankers	Total self-propelled	Total
Avg p/ Power Unit (Short tons)	26542	35218	28446	2471	7065	51721	4323	
Power Unit %	31%	9%	40%	49%	10%	1%	60%	
Avg Est IFO Cons MT/day				8.20	12	30		
Utilisation				85%	85%	85%		
Est Cons Unit p/a				2,544	3,723	9,308		
Total Cons p/a MT				7,227,646	2,125,833	725,985	**10,079,464**	**10,079,464**

(ref. Marad 2020 – https://www.maritime.dot.gov/data-reports/data-statistics/data-statistics)

Table 4: U.S. domestic fleet emissions

	Dry cargo barges	Tankers	Total nonself-propelled	Dry cargo / passenger	Ferries, railroad car	Tankers	Total self-propelled	Total
CO2 emissions Est. MT p/a	13,837,336	4,598,954	**18,436,290**	21,682,938	6,377,499	2,177,955	**30,238,392**	**48,674,682**

(ref. Marad 2020 – https://www.maritime.dot.gov/data-reports/data-statistics/data-statistics) and Core Power.

As shown in Table 4, the U.S. waterborne fleet currently emits approximately 50 million metric tons of CO2 each year, where 18.5 million tons (38%) are emitted by power trains for the movement of the non-self-propelled fleet. The largest portion of those emissions are from the movement of dry cargo barges at 14 million tons, transporting coal, grains, and other non-liquid cargoes on U.S. rivers.

A further 30 million tons, or 62%, of U.S. waterborne fleet emissions are emitted by the self-propelled fleet. That fleet is dominated by dry cargo and passenger vessels emitting an estimated 22 million tons per year. These include vessels of the Jones Act fleet trading between ports on the coast of the U.S.

The fleet also consists of 'medium' sized tankers, bulk carriers, and container ships transporting commodities and goods domestically, as well as some larger tankers transporting oil from Alaskan oil fields to refineries in the continental U.S.A.

Figure 3: Container ship at berth at Long Beach California (Photo: Porttechnology.com)

3.2.1. The Jones Act fleet

Trade between U.S. mainland ports as well as between the U.S. mainland and U.S. territories like Puerto Rico is governed by the Jones Act. The U.S. fleet involved in coastal trading is dominated by tankers that transport crude oil as well as refined oil products.

The Jones Act is a federal U.S. law that regulates maritime commerce in the United States. The Jones Act, also known as Section 27 of the Merchant Marine Act of 1920, requires goods shipped between domestic ports to be transported on ships that are built, owned, and operated by United States citizens or permanent residents. The Act provides for the maintenance of the American merchant marine industry. It regulates the transit of all goods between U.S. ports, preventing foreign flagged, owned, or operated ships to carry out cabotage business in the U.S. or between U.S. territories, excluding the U.S. Virgin Islands, American Samoa, and the Northern Mariana Islands.

Figure 4: Crowley Maritime Corporation Con-Ro ship MV El Coqui Photo: Maritime Executive (https://www.maritime-executive.com/article/crowley-s-lng-fueled-conro-ships-named-significant-boat-of-the-year)

The initial intention of the Jones Act was to protect U.S. shipyards from competition and maintain shipyard capacity for naval purposes. As these vessels must be crewed by American sailors, it would also provide a pool of seafarers for potential naval recruits. While partially successful as a protectionist measure, the number of Jones Act vessels has fallen in recent decades.

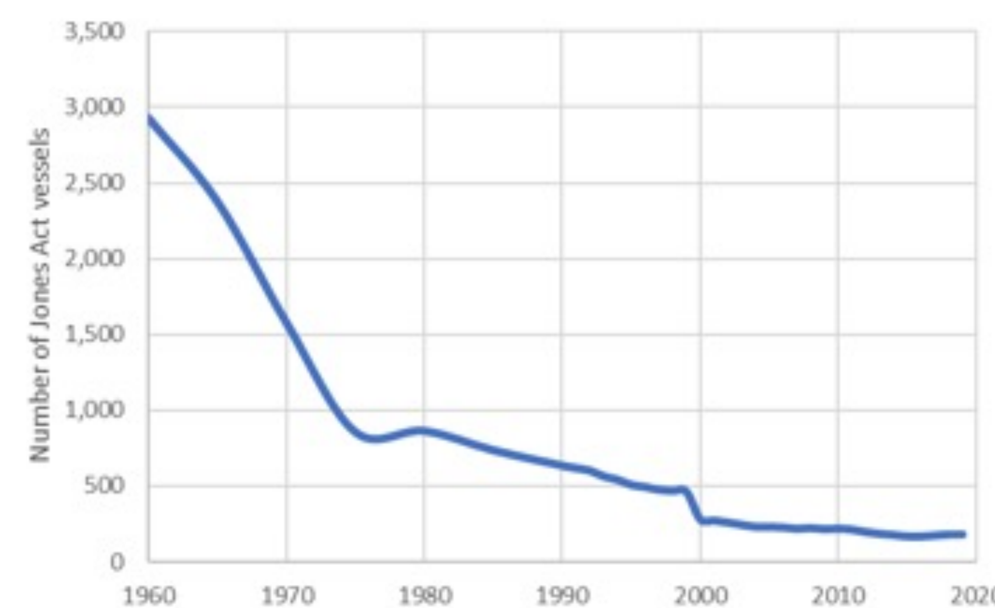


Figure 5: Number of registered vessels in the Jones Act fleet larger than 1,000 gross tons.

The Jones Act fleet has a considerably older age profile than the global fleet. As of 2021 the average age of Jones Act vessels was 18 years with the oldest vessel being 54. This may be due to the inland vessel population. Vessels operating in freshwater are not subject to the same level of saltwater corrosion as oceangoing vessels and can therefore survive longer without major repairs.

Only a quarter of the U.S. fleet is under 10 years old. A typical lifespan of a vessel in the international deep-sea fleet is 20-25 years.[i]

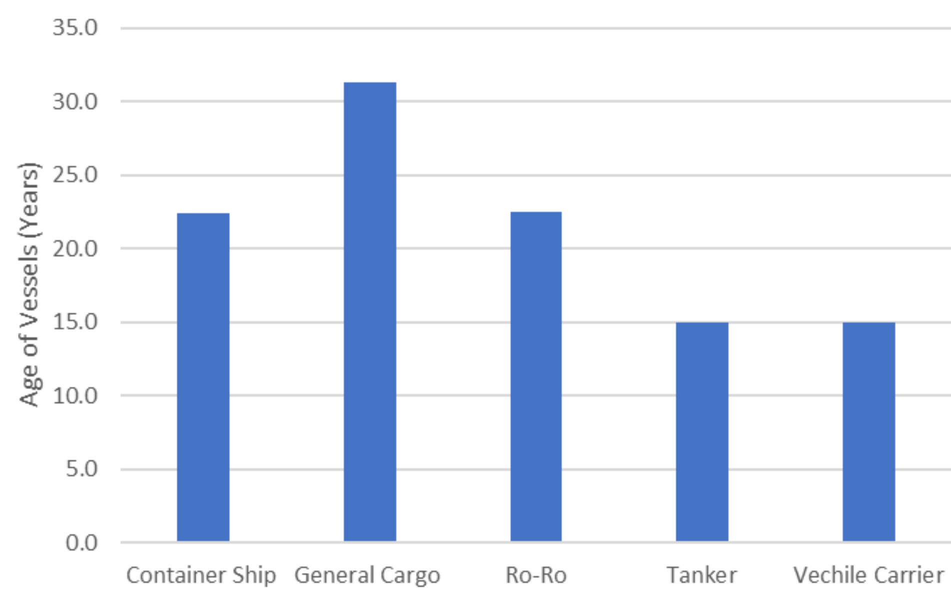


Figure 6: The average age of the Jones Act fleet vessels over 1,000 GT in years by vessel type

The aging of the fleet is also reflective of the reduced orders for new Jones Act Vessels. This is in part due to the high capital expenditure (CAPEX) resulting from the Jones Act's requirement to build ships in domestic yards. Due to changing environmental regulations and uncertainty in national marine environmental policy, owners are hesitant to order new long-lived Jones Act vessels before they select the required or most appropriate propulsion method.

Due to the increased competition of land-based trade routes, the coastal Jones Act fleet is almost entirely used for trade where land-based options are not possible, such as trade from the continental U.S. to Alaska, Hawaii, and Puerto Rico. This ocean-going fleet of vessels has decreased from more than 400 in 1950 to just 100 in 2018, although the total DWT of the vessels engaged in this trade has remained relatively unchanged as ships have become larger.

3.2.2. The Great Lakes Fleet

The Great Lakes provide a marine link between several highly populated areas and manufacturing hubs including Chicago, Detroit, Toronto, and Montreal. Over 160 million tons of cargo valued at $77 Billion is transported on the Lakes each year including agricultural, mining and energy commodities. This fleet of vessels is of special importance to the U.S. steel sector which relies on a fleet of steel-carrying barges to move finished products.[ii]

The vessels undertaking this trade are normally below 300m length overall (LOA) and capable of carrying up to 80,000 metric tons of cargo. Access to industrial ports on the Great Lakes from the Atlantic Ocean through the St. Laurence Seaway is also important for international trade for those areas. Vessels can leave and enter the Great Lakes, though their size is limited by the design constraints of the lock systems along the Seaway and between lakes. The St. Laurence Seaway has a maximum vessel size of 257m LOA and 24m Beam. This means that the largest vessels on the Lakes spend their entire operating lives confined there. Smaller vessels can leave and pass through the Seaway and move goods to international ports around the world.[iii]

3.2.3. The Inland Waterways Fleet

The U.S. has approximately 12,000 miles of commercially navigable waterways. These are typically traversed by arrays of tugboats pushing flat-bottom barges transporting a wide range of goods. Moving goods on the U.S. waterways is one of the most economically efficient ways to transport energy, commodities, industrial components and building materials across the U.S. with transport costs 50% lower than rail and as much as 95% lower than trucks.

In 2019, the Mississippi river system transported 630 million tons of goods.[iv,v,vi]

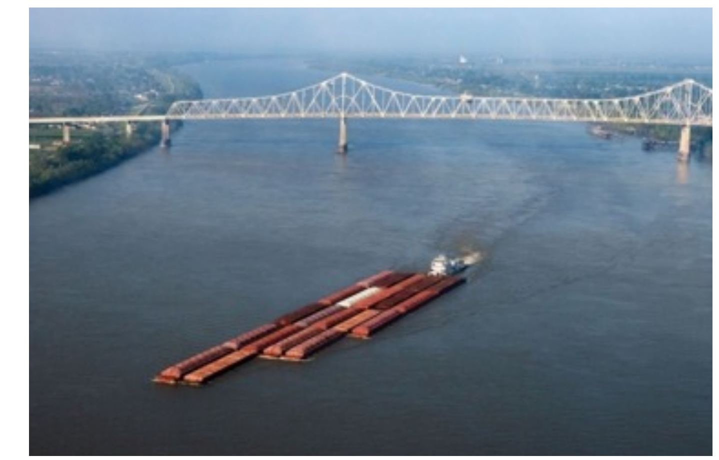


Figure 7: River barge on the Mississippi, Photo: Encyclopedia Brittanica

Figure 8: Map of navigable inland and intracoastal waterways of the U.S.[iii]

3.2.4. The U.S. Maritime Market

The domestic U.S. maritime market is a $50 billion per year coastal and inland waterways transportation industry, as shown in Table 5 (ref. Marad 2020 – [https://www.maritime.dot.gov/data-reports/data-statistics/data-statistics)](https://www.maritime.dot.gov/data-reports/data-statistics/data-statistics)

Table 5: Domestic U.S. maritime market revenues

	2016	2017	2018	e 2019	e 2020	e 2021
Operating revenues (millions of dollars)	**42,806**	**(R) 42,231**	**45,950**	**47,099**	**48,276**	**49,483**
Domestic freight, total	14,614	(R) 13,684	14,463	14,825	15,195	15,575
Coastal and Great Lakes	6,872	6,505	6,784	6,954	7,127	7,306
Inland waterways	7,742	(R) 7,179	7,679	7,871	8,068	8,269
International freight [a]	7,656	6,167	6,426	6,587	6,751	6,920
Passenger, total	20,536	(R) 22,380	25,061	25,688	26,330	26,988
Domestic passenger	844	959	1,041	1,067	1,094	1,121

Notes:

a. The international water freight operating revenues data was revised in Transportation in America 1998 for all years except 1994 and 1996. Therefore, the international water freight data for years 1994 and 1996 may not be comparable to other years.

b. Revenues paid by American travellers to U.S. and foreign flag carriers.

(ref. Marad 2020 – https://www.maritime.dot.gov/data-reports/data-statistics/data-statistics & https://www.census.gov/programs-surveys/sas.html as of Feb. 11, 2020)

The sector employs almost 300,000 workers across the Great Lakes, the U.S. inland waterways, and on coastal trades under the Jones Act of 1920, a federal law that regulates maritime commerce in the United States. See Table 6.

Table 6: U.S. domestic maritime employment

Number of employees	2016	2017	2018	e 2019	e 2020	e 2021
Ship and boat building [c]	135,500	134,500	138,700	141,474	140,059	138,659
Water transportation [c]	157,400	156,800	159,900	163,098	161,467	159,852
Total Jobs	292,900	291,300	298,600	304,572	301,526	298,511

Notes:

c. Data is based on NAICS classifications. Data for water transportation in 2002 includes NAICS categories 483100, 483200, 488300. Data for ships, boat building, and repairing is based on the NAICS category 336600.

b. Revenues paid by American travellers to U.S. and foreign flag carriers.

(ref. Marad 2020 – https://www.maritime.dot.gov/data-reports/data-statistics/data-statistics & US Bureau of Labor Statistics http://www.bls.gov as of May 11, 2020)

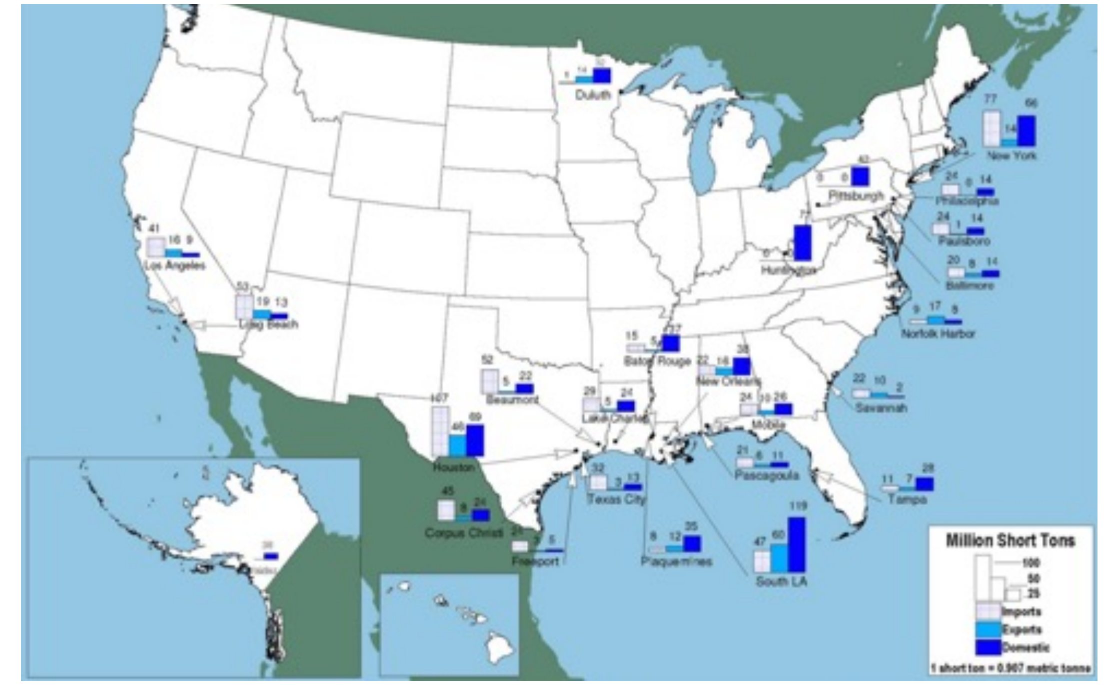


Figure 9: Cargoes handled in US ports in 2020. Source Wikipedia (https://en.wikipedia.org/wiki/List_of_ports_in_the_United_States)

3.3. Ship Types

Globally, there are approximately 65,000 large, medium, and small ships with lengths over 100 meters. These comprise tankers carrying liquid and gaseous cargos, bulkers carrying dry bulk commodities, container ships carrying standardized 20- and 40-foot containers, Roll-on-Roll-off (RoRo) ships carrying cars, trucks, and agricultural machinery, and cruise ships and ferries carrying passengers and vehicles. A further fleet of offshore support vessels, project cargo ships, and specialist vessels augment this global fleet. Figure 10, Figure 11 and Table 7 below summarize this global fleet by capacity and size.

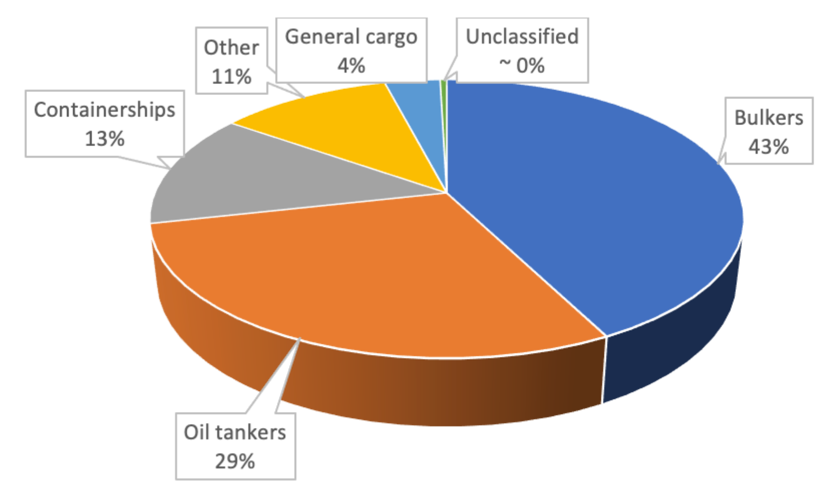


Figure 10: Ship Type by DWT (2020), Source: UNCTADstat (UNCTAD, 2021); Clarksons Research, CORE POWER, Note: Commercial ships of 100 GT and above. Beginning-of-year 2020 figures.

In the last century, gas carriers have experienced the fastest growth followed by oil tankers, bulk carriers, and container ships. The size of the largest container vessel in terms of capacity has increased rapidly. The largest container ships are now as big as the largest oil tankers and bigger than the largest dry bulk and cruise ships.

Ships carrying cargo in bulk, like liquid tankers and bulkers, are measured and categorized in size by 'deadweight tons' or the total weight of the cargo they are designed to carry safely. Gas tankers are categorized by their cubic capacity for gas storage onboard. Container ships are categorized by the number of twenty-foot equivalent units (TEUs) they can carry. Passenger ships are measured in their gross registered tons, which is the total weight of the hull and all the machinery and fittings onboard before cargo, and the number of passengers they can accommodate. Specialist vessels for offshore support and project cargo are typically categorized by metrics relevant to their specific work such as lifting capacity, length, or power.

Overall, the global fleet has seen a compound aggregate growth rate of about 2% over the last 30 years, aligned with the growth in global trade and demand for efficient ocean transportation.

In each of the sub-sectors of shipping, there are a variety of different ship sizes which are either built to carry specific cargoes or operate in specific regions and trade routes. Additional information on different ship types can be found in Appendix A.

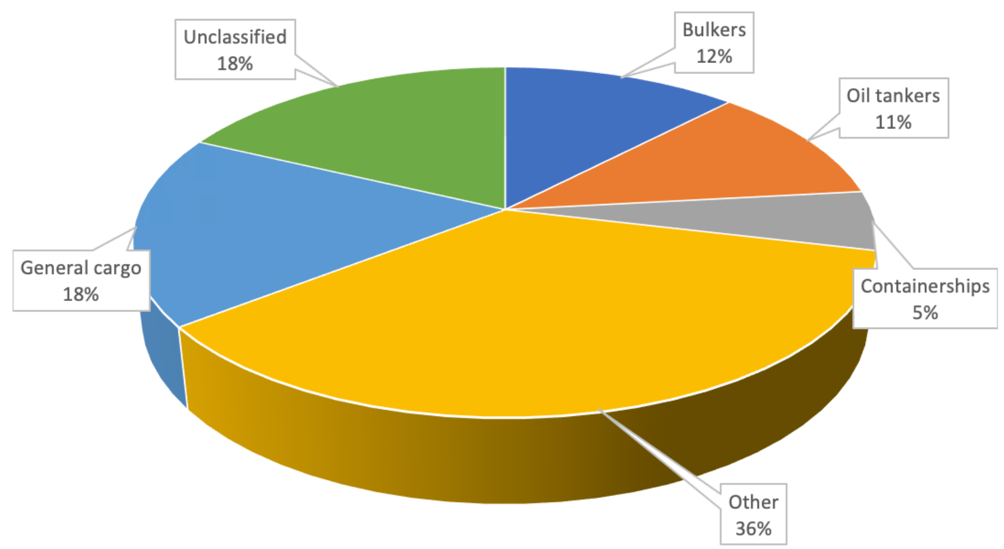


Figure 11: Number of Ships (2020), Source: UNCTADstat (UNCTAD, 2021); Clarksons Research, CORE POWER, Note: Commercial ships of 100 GT and above. Beginning-of-year 2020 figures.

Table 7: Size and Age Profile of the Global Fleet

Bulk carriers	**Age 0-4 Years**	**Age 5-9 Years**	**Age 10-14 Years**	**Age 15-19 Years**	**Age >20 Years**	**Total**
Total number of ships	2,419	5,046	2,237	1,075	1,189	**11,965**
Percentage of total ships	20%	42%	19%	9%	10%	
Average vessel size (dead-weight tonnage)	84714	78169	65767	67246	50973	
Total DWT	204,883,890	394,467,438	147,111,909	72,280,926	60,585,837	**879,330,000**
Percentage of dead-weight tonnage	23%	45%	17%	8%	7%	
Oil tankers						
Total number of ships	1,593	2,059	2,237	1,221	3,756	**10,867**
Percentage of total ships	14%	19%	20%	11%	35%	
Average vessel size (dead-weight tonnage)	93311	72952	71391	86251	9924	
Total DWT	148,667,610	150,230,634	159,729,009	105,323,758	37,272,106	**601,223,116**
Percentage of dead-weight tonnage	25%	25%	27%	18%	6%	
Container ships						
Total number of ships	838	1,095	1,761	788	889	**5,372**
Percentage of total ships	16%	20%	33%	15%	17%	
Average vessel size (dead-weight tonnage)	80070	73137	43993	40934	20186	
Total DWT	67,092,350	80,093,038	77,481,906	32,268,094	17,948,097	**274,883,486**
Percentage of dead-weight tonnage	24%	29%	28%	12%	7%	
Other						
Total number of ships	4,307	6,271	5,938	3,052	15,477	**35,046**
Percentage of total ships	11%	18%	16%	8%	47%	
Average vessel size (dead-weight tonnage)	11613	6267	8682	8034	4304	
Total DWT	50,022,003	39,303,002	51,553,289	24,523,774	66,610,932	**232,013,000**
Percentage of dead-weight tonnage	22%	17%	22%	11%	29%	
General cargo ships						
Total number of ships	801	2,151	2,702	1,249	10,410	**17,312**
Percentage of total ships	5%	12%	16%	8%	59%	
Average vessel size (dead-weight tonnage)	7933	8029	5455	5902	2772	
Total DWT	6,354,472	17,273,423	14,737,601	7,368,800	28,856,163	**74,590,458**
Percentage of dead-weight tonnage	9%	23%	20%	10%	39%	
Total world fleet						
Unclassified					*17,578*	
Total ships	**9,958**	**16,624**	**14,875**	**7,385**	**31,720**	**98,140**
Unclassified					9,000,000	
Total DWT	**477,020,324**	**681,367,535**	**450,613,714**	**241,765,353**	**211,273,135**	**2,071,040,060**

Source: UNCTADstat (UNCTAD, 2021); Clarksons Research, CORE POWER Note: Commercial ships of 100 gt and above. Beginning-of-year 2020 figures.

3.3.1. Oil Tankers

Tankers as a total fleet carry approximately 38% of the total bulk of cargoes. Tankers move approximately 2.0 billion metric tons of oil every year, second in efficiency only to pipelines. The average cost of the transport of crude oil by tankers amounts to U.S. $5 to $8 per cubic meter ($0.02 to $0.03 per US gallon).

This tanker fleet is sub-divided into categories as shown in Figure 12.

More details of the breakdown of the global fleet ship types and sizes is included in Appendix A.

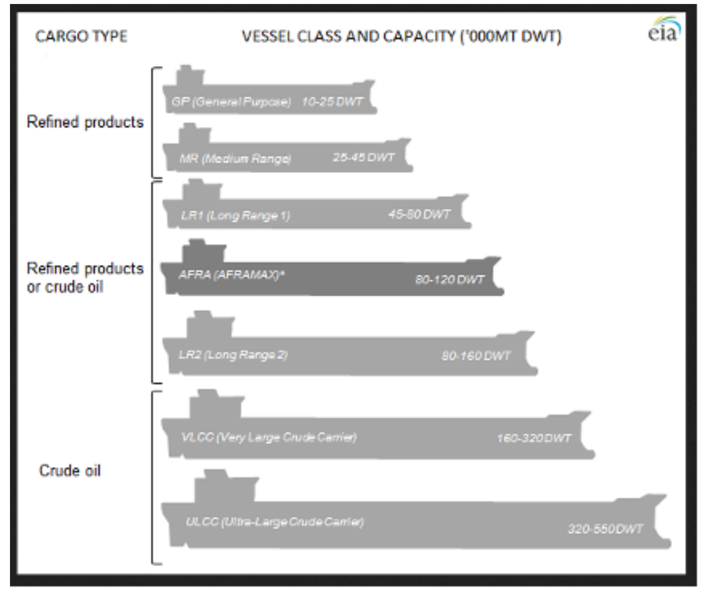


Figure 12: Tanker Vessel Sizes and Capacities Source: https://mycompassair.com/part-3-vessels/

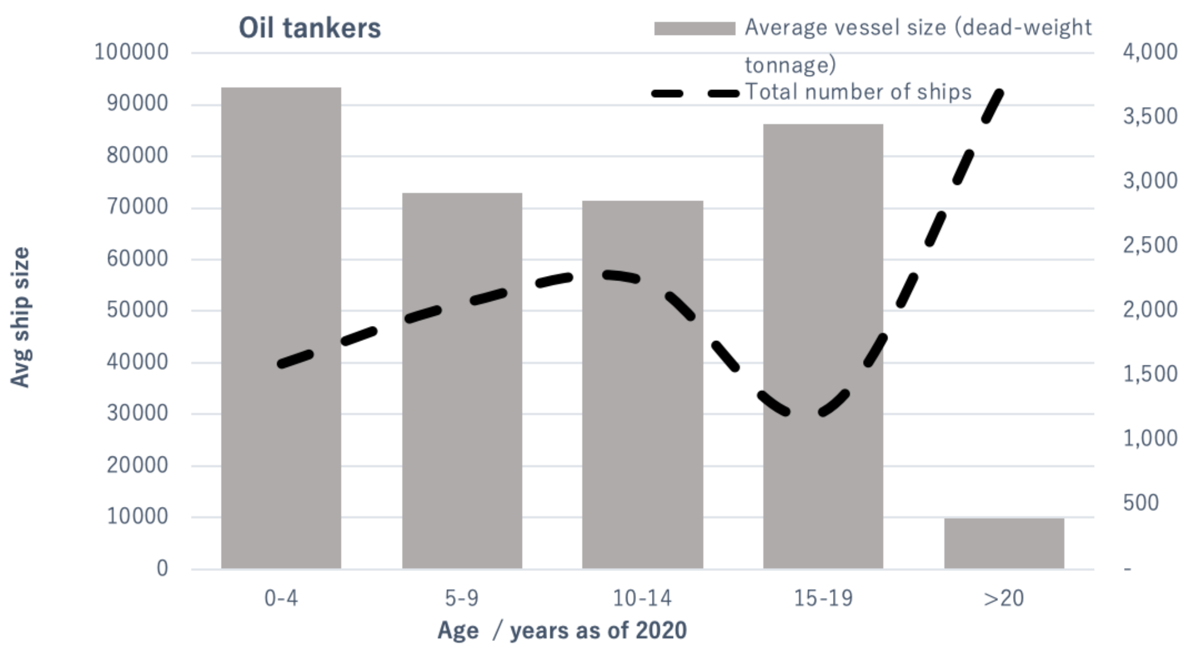


Figure 13: Oil Tankers Size versus Age, Source: UNCTADstat (UNCTAD, 2021); Clarksons Research, CORE POWER, Note: Commercial ships of 100 GT and above. Beginning-of-year 2020 figures.

3.3.2. Gas Tankers

Gas tankers are classified by their carrying capacity of specific gases.

In general, the most common gas cargoes are liquified petroleum gas (LPG) extracted from petroleum reserves and liquified natural gas (LNG) extracted from hydrocarbon deposits near fossil fuels.

LNG carriers are typically between 125,000 and 135,000 m3 in capacity. The total gas carrier fleet is about 74 million deadweight tonnes, making up 4% of the global fleet carrying capacity.

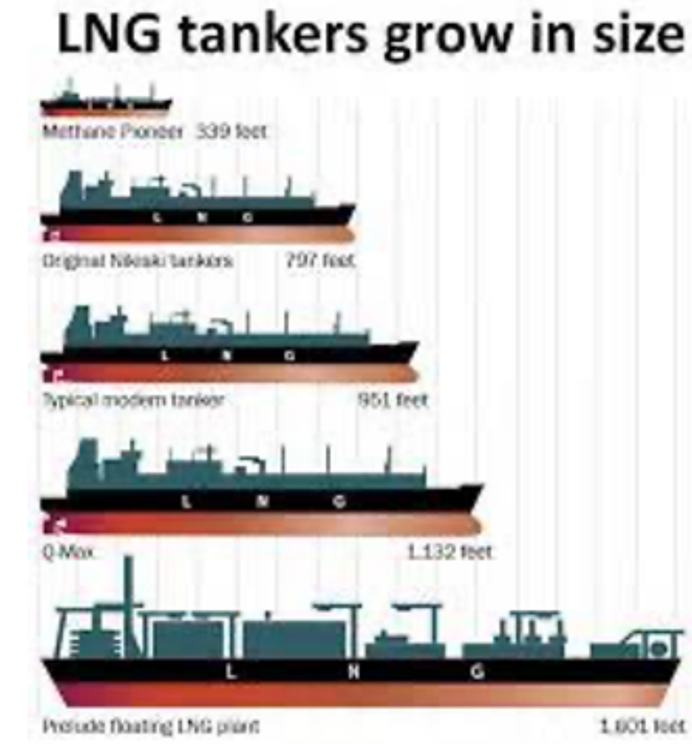


Figure 14: LNG Tanker Types and Sizes

3.3.3. Dry Bulk Ships

A dry bulk ship or bulker is a ship specially designed to transport unpackaged bulk cargo, such as grain, coal, ore (major bulks) or bauxite, building materials, and sand or other loose materials (minor bulks) in its cargo holds.

Bulkers are classified by their cargo-carrying capacity or deadweight tons (DWT) as well as whether the ship can self-load and unload by using its cranes fitted onboard or if it requires external shore gear for cargo operations.

The swift growth of trade in dry bulk commodities has been accompanied by the rapid industrialization of China that accelerated with its accession to the World Trade Organization (WTO) in 2001.

Bulk carriers make up 21% of the world's merchant fleets and range in size from single-hold mini-bulk carriers to huge ore ships able to carry as much as 400,000 metric tons of cargo. 82% of all bulkers in the global fleet were built in Asia.

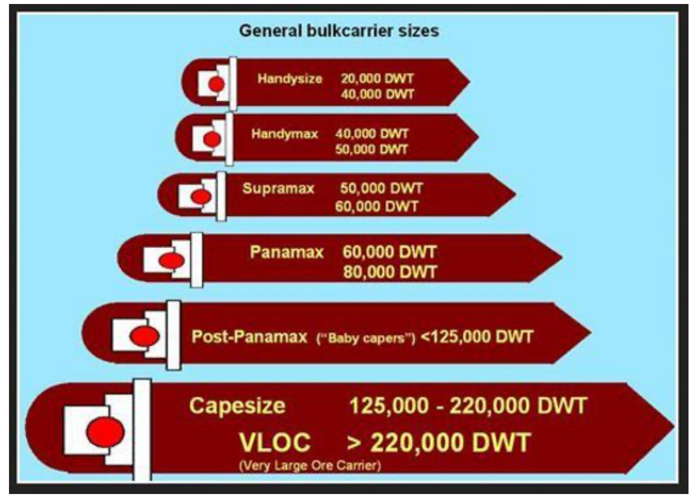


Figure 15: Bulk Carriers Sizes and Capacities https://mycompassair.com/part-3-vessels/

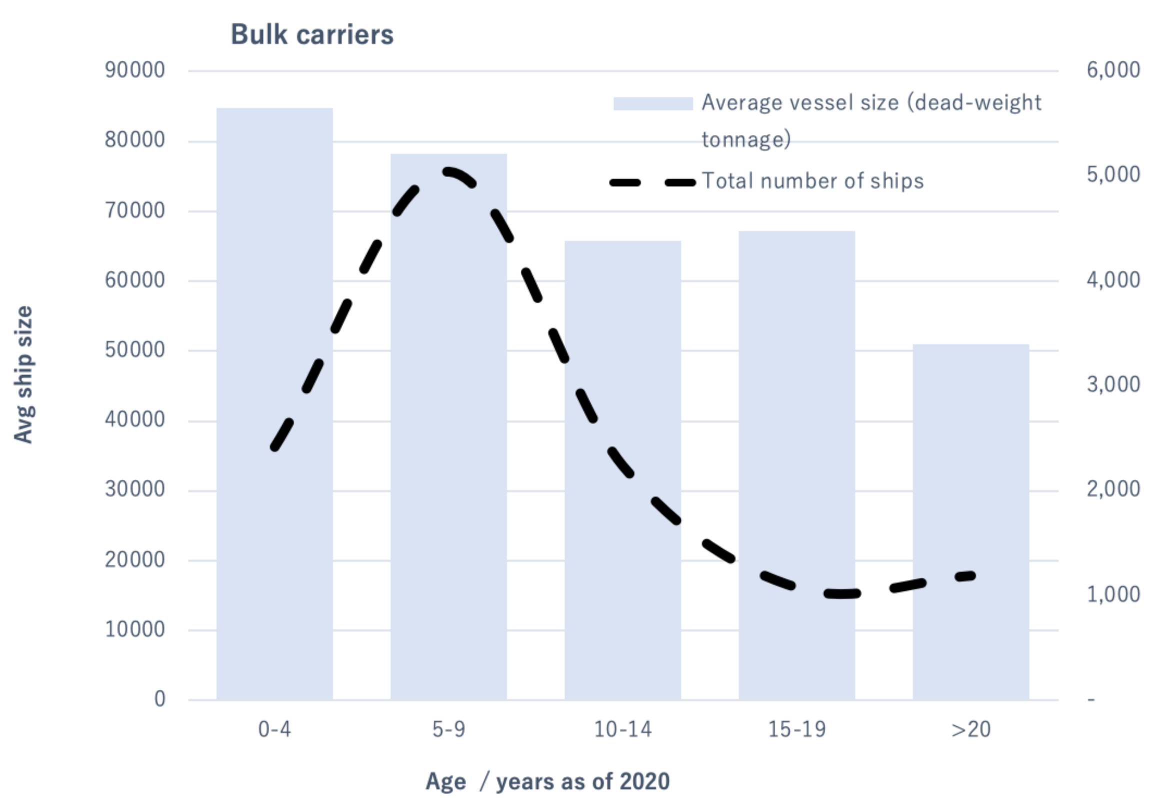


Figure 16: Bulk Carriers Size versus Age, Source: UNCTADstat (UNCTAD, 2021); Clarksons Research, CORE POWER, Note: Commercial ships of 100 gt and above. Beginning-of-year 2020 figures.

3.3.4. Container Ships

Growth in maritime trade over the past three decades has been sustained by bullish trends in containerized trade volumes starting in the 2000s coinciding with the wave of hyper globalization.

A container ship (also known as a boxship) carries its cargo in truck-size intermodal containers, in a technique called containerization. Container ships now represent as much as 90% of ocean-going non-bulk cargo. Container ship capacity is measured in twenty-foot equivalent units (TEU) where 40-foot (2-TEU) ISO-standard containers are predominant.

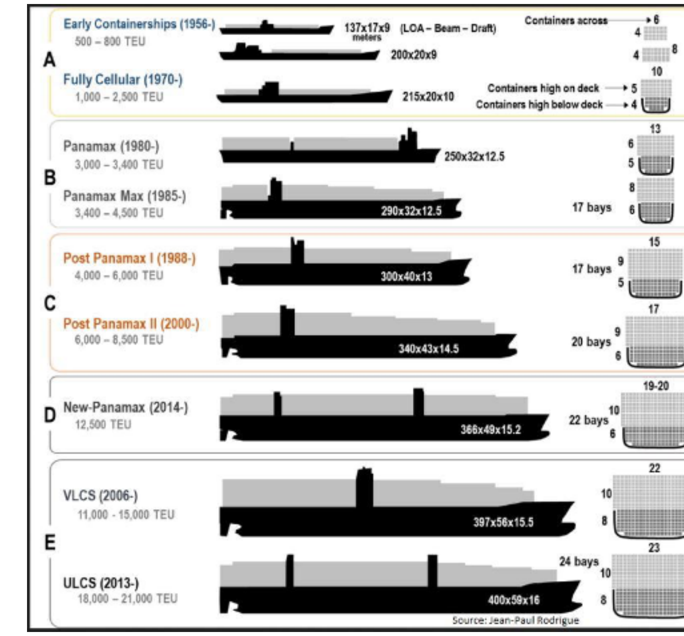


Figure 17: Container Ship Types and Capacities https://mycompassair.com/part-3-vessels/

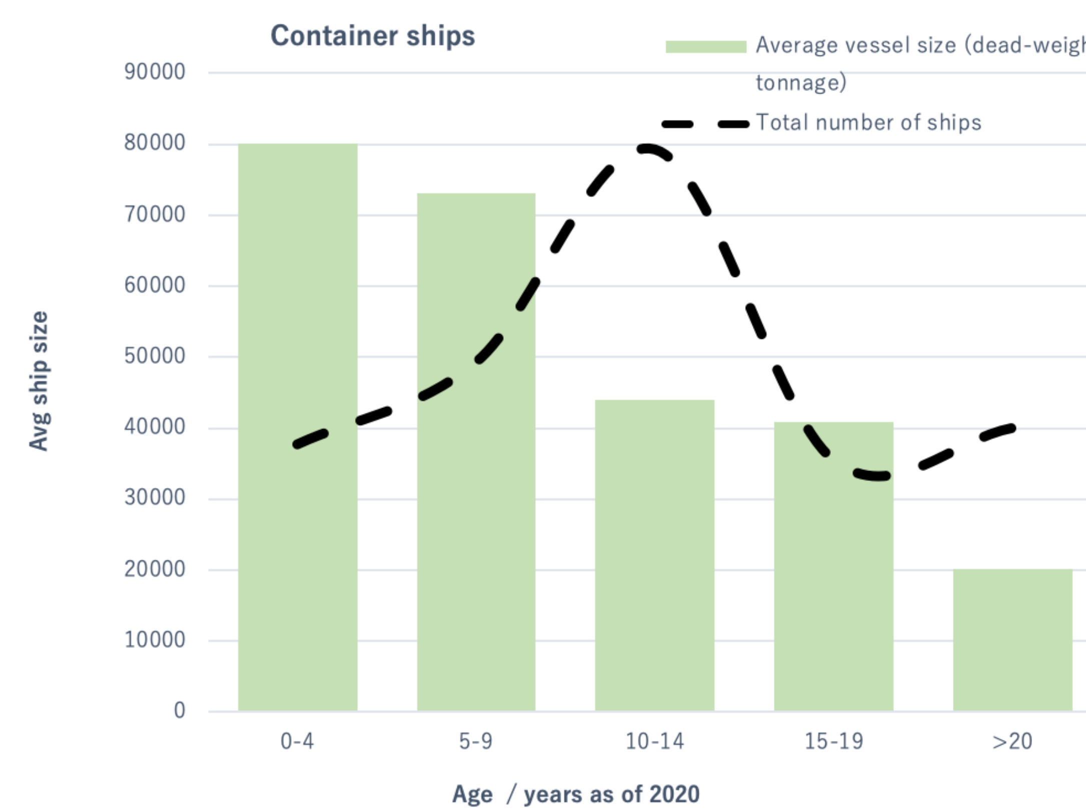


Figure 18: Container Ships Size versus AgeSource: UNCTADstat (UNCTAD, 2021); Clarksons Research, CORE POWERNote: Commercial ships of 100 gt and above. Beginning-of-year 2020 figures

3.3.5. Passenger Ships

A passenger ship is a merchant ship whose primary function is to carry passengers. While typically passenger ships are part of the merchant marine, passenger ships have also been used as troopships and are commissioned as naval ships when used for that purpose.

Passenger ships include ferries, ocean liners and cruise ships. Ferries move passengers and vehicles (whether on road or rail) over various lengths of water. Ocean liners are typically passenger or passenger-cargo vessels transporting passengers and often cargo on longer line voyages. Cruise ships often transport passengers on round-trips, in which the trip itself and the attractions of the ship and ports visited are the principal draw.

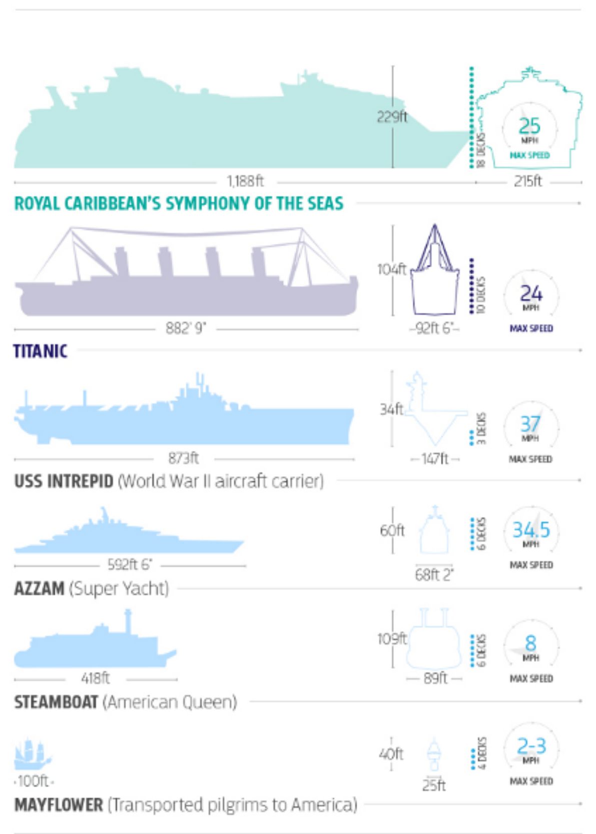


Figure 19: Passenger Ship Types and Sizes

3.3.6. Other Ships

Ro-Ro Vessels are named for their roll-on, roll-off capability to load cars and trucks, either for vehicle transport or as a part of a ferry service. They are distinguished by one or more ramps for vehicle loading.

Offshore Service Vessels (OSVs) generally serve offshore installations or activities related to offshore oil & gas exploration and exploitation, including transporting crew, supplying fuel and provisions or installing or handling anchors and other mooring equipment.

Icebreakers are often multi-purpose vessels with the key feature of strengthened and specially shaped bows designed for breaking through sea or lake ice up to several meters deep.

Research Vessels are also multi-purpose vessels and commonly owned by national entities for research and sea exploration. Many research vessels are involved in relatively small, coastal operations for scientific expeditions and data collection.

Figure 20: USCG Polar Sea, CCG icebreaker Louis St. Laurent and Russian Icebreaker Yamal near the north pole in 1994. USCG Photo

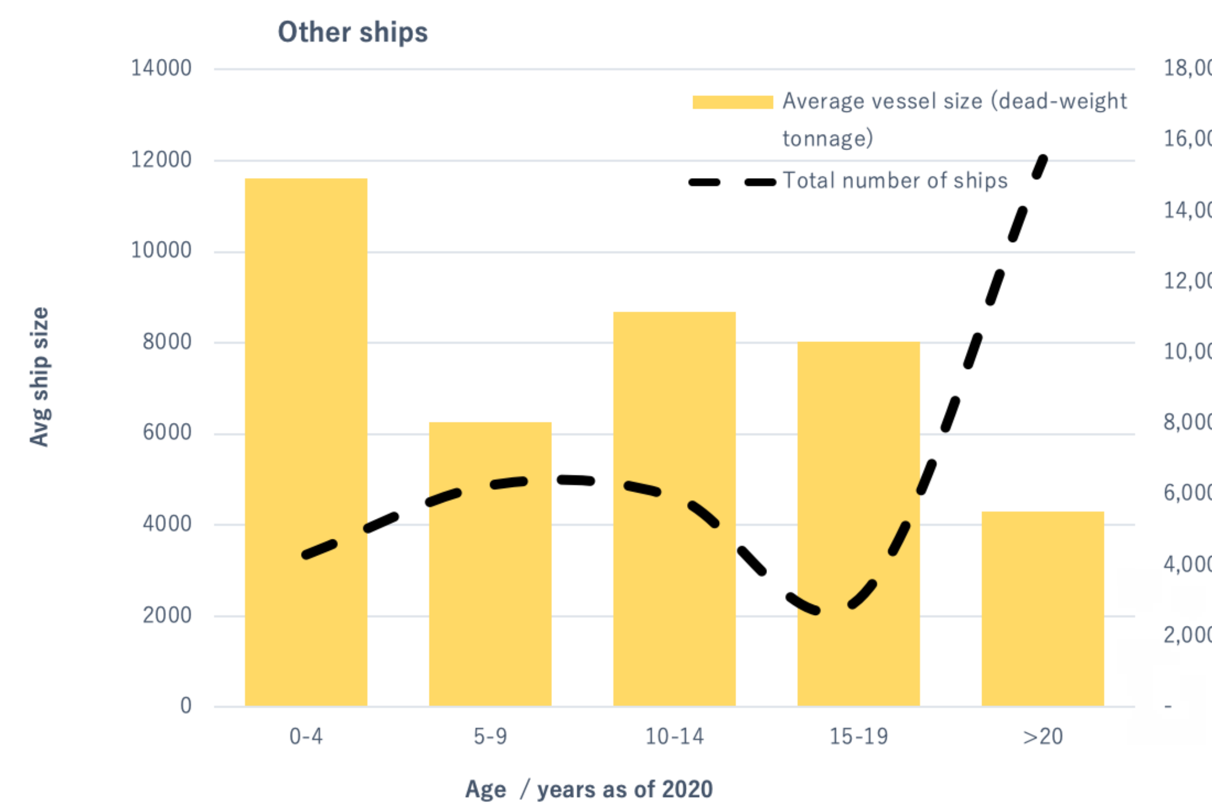


Figure 21: Other Ship Sizes versus Age, Source: UNCTADstat (UNCTAD, 2021); Clarksons Research, CORE POWER, Note: Commercial ships of 100 gt and above. Beginning-of-year 2020 figures.

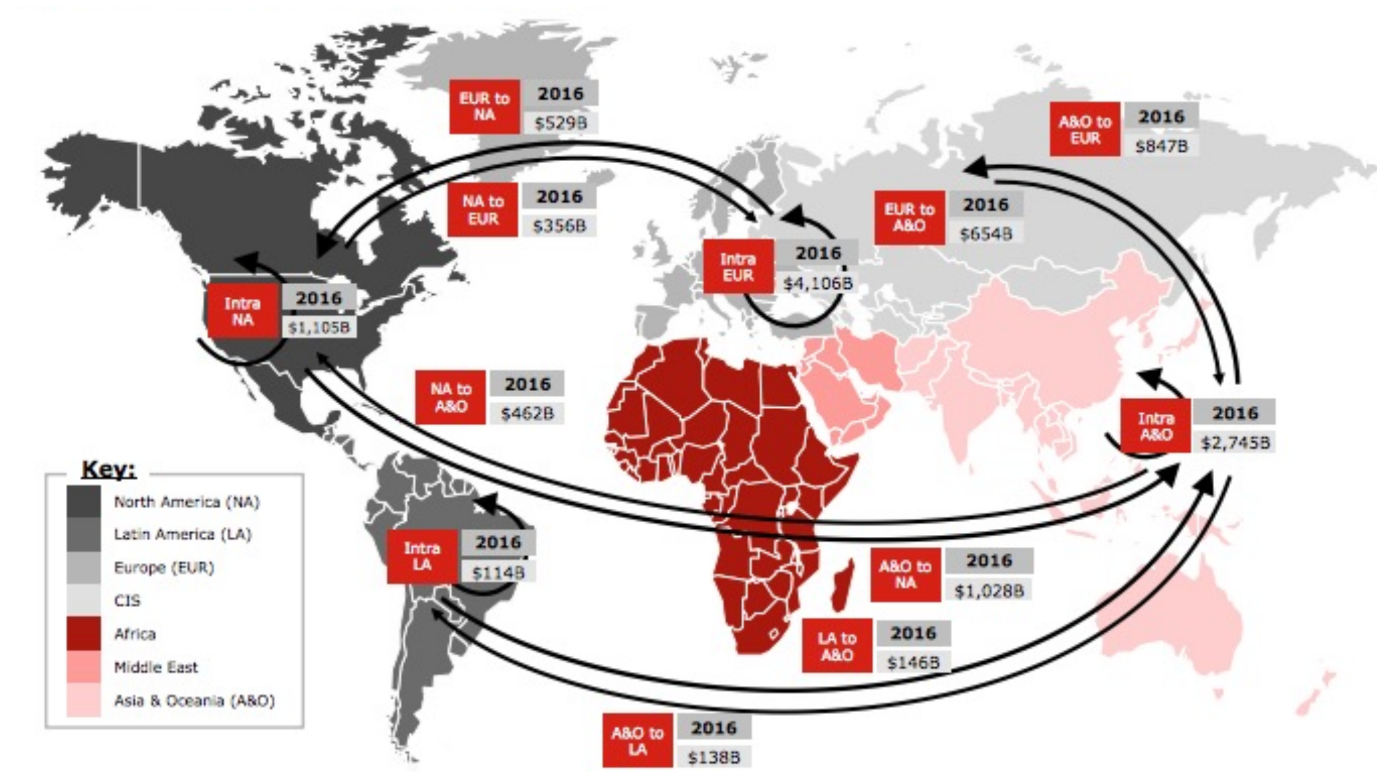
3.4. Growth in Trade

When adjusted for distance travelled, Clarksons Research estimates total seaborne trade to be 59,503 billion ton-miles in 2019. The fastest growth was seen in the trade of LNG which increased by 11.9% between 2018 and 2019, supported by project start-ups in Australia and the United States.

Agricultural bulk commodities, notably grain, are an important issue in trade politics. In 2018, Brazil overtook the United States as the world's largest seaborne grain exporter. In 2019, grain volumes expanded by just 0.4%, and soybean imports into China accounted for about 60% of all global soybean trade.

The continued prominence of Asia as the world's center of manufacturing continued to boost expansion in intra-Asian container trade, with a growing contribution from South-East Asia. Secondary East-West trade routes and North-South routes accounted for 13.1% and 7.9% (Unctad Stats: 2020) of the market. These trades are the East-West routes involving flows between the Far East and Western Asia, the Far East and South Asia, South Asia and Europe, and Western Asia and Europe.

Shifts in consumption and shipping patterns with the rise of e-commerce are likely to continue. The COVID-19 pandemic revealed how e-commerce can be an important instrument to sustain economic resilience during crises. The pandemic and associated lockdowns may have boosted e-commerce uptake, which may continue as consumption patterns evolve.



Source: WTO world region export analysis, October 2017; Bain & Company analysis

Figure 22: Global Trade Flows

In 2018, UNCTAD stated global e-commerce sales $25.6 trillion, which includes business-to-business and business-to-consumer sales. This was equivalent to 30% of global GDP. The United States continued to dominate the overall e-commerce market and remained among the top three countries in business-to-consumer e-commerce sales, along with China and the United Kingdom (UNCTAD, 2018).

Emissions from maritime trade are increasingly coming into focus in the supply and value chains of durable consumer goods. The introduction of carbon pricing and potential upcoming requirements for retailers to report the carbon footprint of goods sold will for the first time show the environmental impact of ocean transportation on consumer goods, industrial components, and bulk commodities, providing a strong international impetus for shipping to decarbonize and move into a future of sustainable zero-emission propulsion.

3.5. Lifecycle and Certification of Ships

The lifecycles of a ship include design, shipyard construction, commissioning, operations, and recycling or scrapping at end of life. Many stakeholders are involved in the lifecycle of a vessel, from designers, shipbuilders, owners, charterers, registered Flag administrations, classification societies, shipboard crew, cargo brokers, port authorities, and ship recycling facilities.

All commercial ships of 500 Gross Tonnes or larger, engaged in international voyages, are subject to the IMO International Convention for the Safety of Life at Sea (SOLAS), 1974, and its Protocol of 1988 and are required to be built, constructed and maintained to the Rules of a Classification Society. Any vessel designed and built to the appropriate Rules of a Classification Society may apply for and receive a Certificate of Classification.

Classification Societies verify that the construction of a marine vessel or offshore installation complies with relevant standards, and they also conduct regular in-service surveys to verify ongoing compliance.

Figure 23: Shipyard photo courtesy of gCaptain (https://gcaptain.com/15-incredible-shipyard-photos-and-pictures/)

Classification Societies provide classification and statutory services. This includes publishing standards in the form of Rules. Many Classification Societies are members of the International Association of Classification Societies (IACS), which publishes unified interpretations derived from statutory international regulations adopted by the IMO.

In the IMO, international standards and regulations are developed and adopted through technical working groups and committees involving member nations, technical experts or communities, non-governmental organizations, and other stakeholders in the international maritime industry. It is the responsibility of IMO Member states to adopt resolutions and enforce them.

IACS interprets the IMO standards for Classification Societies to integrate into their own rules and guides for the design, construction, and survey of ships and offshore installations.

The objective of ship classification is to verify the structural strength and integrity of essential parts of the ship's hull and appendages, and the operability of the propulsion and steering systems, power generation and those other features and auxiliary systems onboard which maintain essential and auxiliary services on board. Classification Societies achieve this objective through the development and application of their Rules and by verifying compliance with those Rules as well as international and/or national statutory regulations on behalf of Flag Administrations. Classification Societies may also be a recognized organization to carry out national maritime administration verification work, such as that of the U.S. Coast Guard.

Ships and offshore installations are therefore required to have a survey conducted periodically to verify compliance with relevant standards and Class rules. Annual surveys verify a ship's condition and its ability to maintain Class. Intermediate surveys typically happen every 2-3 years and may investigate ship structure, equipment, and onboard procedures more thoroughly than the annual survey. Special surveys are conducted every 5 years, and usually determine the detailed condition of the asset. Special surveys may be related to periodic drydocking for hull inspections and other large modifications or repairs.

It is commonly accepted that most large ships trading internationally can go through a certain number of special surveys before they are no longer considered economically viable for operating. This is generally due to the deterioration of ship conditions regarding structural corrosion, loss of equipment or system functionality, or obsolete functionality or operability.

Figure 24: Ship breakers – Courtesy of https://www.theatlantic.com/photo/2014/11/the-ship-breakers/100859/

Generally, the following rule of thumb for the expected life of vessels is applied.

Tankers: after 2-4 special surveys = 15-25 years

Bulkers: after 3-5 special surveys = 25-30 years

Container ships: after 3-5 special surveys = 25-30 years

Passenger ships: after 5-7 special surveys = 30-40 years

According to UNCTAD, as of 2020, the average age of all ships in the world merchant fleet was just over 20 years. General cargo ships were the oldest vessel type, with an average age of around 26 years; over 65% of the world's cargo ships were older than 14 years, in contrast with just 18% of bulk carriers.

Figure 25: Ship emissions – Courtesy of Roberto Venturini (via Flickr)

3.6. Lifecycle Emissions from Ships and Offshore Structures

The term 'sustainability' is expanding the way the marine industry considers emissions from ships and offshore structures as it includes the lifecycle of the asset and all the energy used during its operating lifetime. The lifecycle analysis of emissions therefore includes not only the emissions during fuel consumption for power and propulsion, but also the total emissions produced during ship construction and recycling and emissions from fuel production over the ship's lifetime.

The emissions from material production, shipbuilding maintenance, transportation and end of life pollutants are relatively small compared to those emissions produced during ship operation. Specifically, these include the emissions from methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) produced in internal combustion engines or other chemical processes regarding fossil fuels to extract power or raw material. With lifespans up to 40 years or longer, the fuel consumed to power ships and offshore structures over their lifetimes can contribute to a significant percentage of total lifetime emissions. For this reason, emissions monitoring for ship fuel and reduction of emissions from the lifecycle of the fuel itself may be important to consider the overall sustainability of the vessel.

Emissions from ships and offshore structures typically include both GHG emissions and other pollutants. GHGs include Carbon dioxide (CO2) Methane (CH4), N2O (often generalized as nitrogen oxides, NOX), and fluorinated gases as defined by the U.S. Environmental Protection Agency that trap heat in the Earth's atmosphere. These are often addressed separately from other pollutants which include sulfur oxides (SOX), particulate matter (PM) and other toxic or harmful pollutants.

Figure 26: Container ship emissions – Courtesy of dw.com / Getty Images.

Emissions from ship fuels can be categorized into two main categories:

Well-to-Tank (WTT) Emissions

Well-to-Tank emissions include those emissions produced during fuel production, transportation and handling. Fuel production emissions are those produced during oil extraction, refining, or other production process to create the fuel (e.g., emissions from agriculture and refining in the case of biofuels). Transportation emissions may include those emitted during carriage over land or sea as cargo. Emissions from handling and storage often include those emitted to achieve the energy needed to cool, heat, compress or liquefy the fuel to its appropriate state for use and consumption. Well-To-Tank emissions can also include fugitive emissions from leaks or other indirect emissions sources.

Tank-to-Wake (TTW) Emissions

Tank-to-Wake emissions are those produced during fuel consumption or combustion. They can be characterized as those occurring from fuel delivery to end use and can also include fugitive emissions such as methane slip from LNG engines.

From a regulatory perspective, it is relatively easier to address direct Tank-to-Wake emissions from ships than to enforce reduced Well-to-Tank emissions at multiple points of release from dispersed stakeholders. In recent years, new mandates have been implemented to reduce emissions from ships, including reducing allowable SOx in marine fuel and limiting NOx emissions from ship stacks.

Scrubber systems and exhaust gas recirculation systems can be used to reduce emissions before release. Carbon capture technologies are developing to extract carbon dioxide (CO2) from exhaust gases. Other alternatives include reducing SOx content in fuels and reducing petroleum-sourced carbon by using biofuel substitutes or blending biofuels with marine fuels.

Other alternative fuels may enable carbon-free shipping such as hydrogen or ammonia, or significantly reduce carbon emissions by using methanol, ethanol or methane as marine fuel. However, these alternative energy carriers come with a variety of challenges and hazards including low flashpoint, toxicity, flammability, and low energy density.

Figure 27: Container Ship with tugs – courtesy of https://splash247.com/

From a Well-to-Tank perspective, more work needs to be done to examine the lifecycle emissions of fuels. Some fuels and power options may have significantly higher emissions during production than during combustion or use. Batteries for example provide clean energy in the form of electricity, however, the electricity for charging may be generated from an emissions-intensive process, such as burning coal or combustion of fossil fuels in a power plant.

While batteries may offer energy storage benefits to many vessels, they cannot store enough energy effectively to power large ships alone. Batteries and other energy storage systems will be important in the marine transition to sustainable decarbonization for power optimization.

In addition to onboard handling issues, many alternative fuels also have Well-to-Tank emissions that are prohibitively high and limit widespread adoption of the fuel. For example, e-fuel (i.e., gas or liquid fuels generated from electricity and a feedstock) may produce fuel alternatives such as e-LNG, e-methanol, or e-hydrogen. However, similar to batteries, if the electricity used to produce the fuel is not sourced from renewable or sustainable energy, the resulting energy-carrying fuel may not be considered renewable or sustainable.

There are many recent publications, studies and reports from the marine and energy industries discussing the feasibility, economy, availability, and trade-offs of alternative marine fuels and powering arrangements to substitute or replace fossil-based fuels.

Some notable examples include:

- In March 2019, a group of Dutch multinationals – FrieslandCampina, Heineken, Philips, DSM, Shell and Unilever, all members of the Dutch Sustainable Growth Coalition (DSGC), joined forces with Maersk on a landmark biofuel-powered voyage from Europe to China.

  The pilot, using up to 20% sustainable second-generation biofuels on a large triple-E boxship, sailed 25,000 nautical miles from Rotterdam to Shanghai and back on biofuel blends, a world's first at this scale, saving 1500 tons of CO2 and 20 tons of sulphur.
  https://www.dsgc.nl/en/news/2019/maritime-biofuel-pilot-great-success

- In January 2020, the Global Maritime Forum issued a report to gauge the capital investment needed to achieve decarbonization outcomes in line with the IMO Initial Strategy. The Brief was based on analytical work conducted by University Maritime Advisory Services (UMAS) and Energy Transitions Commission (ETC).

  The report argued that the scale of cumulative investment needed between 2030 and 2050 to achieve the IMO target of reducing carbon emissions from shipping by at least 50% by 2050, is approximately USD $1 - 1.4 trillion, or on average between USD $50 - 70 billion annually for 20 years. This estimate should be seen in the context of annual global investments in energy, which in 2018 amounted to USD $1.85 trillion.

  If shipping was to fully decarbonize by 2050, this would require extra investments of approximately USD $400 billion over 20 years, making the total investments needed between USD $1.4-1.9 trillion dollars.
  https://www.globalmaritimeforum.org/news/the-scale-of-investment-needed-to-decarbonize-international-shipping

- In April 2021, a new series of reports by the World Bank with valuable expert support from University Maritime Advisory Services (UMAS) highlighted that decarbonizing maritime transport offers a unique business and development opportunity for countries, including developing and emerging economies. For developing countries with large renewable energy resources, this could mean tapping into an estimated $1+ trillion future fuel market, while modernizing domestic energy and industrial infrastructures
  https://www.worldbank.org/en/news/feature/2021/04/15/charting-a-course-for-decarbonizing-maritime-transport

- In March 2022, a joint project used onboard techniques and drones to measure methane emissions from ships. The International Council on Clean Transportation (ICCT) is leading the project called Fugitive Methane Emissions from Ships (FUMES), in collaboration with Danish-based Explicit and the Netherlands Organization for Applied Scientific Research (TNO). Using in-stack continuous emissions monitoring, drones, and helicopters, the project aims to examine and quantify methane slip from ships fuelled by liquefied natural gas (LNG) under a variety of real-world operating conditions on a large scale.

  Use of LNG as a marine fuel globally grew nearly 30% between 2012 and 2018 and LNG is becoming popular as a fuel for cargo ships and cruise ships with more than a third of the global orderbook in DWT opting for LNG dual fuel propulsion. While LNG has the ability to reduce carbon emissions, considerations for methane slip are important to consider the full impact and suitability of the alternative fuel.
  https://splash247.com/methane-slip-at-sea-study-commences/

The widely expected imposition of carbon taxes in years to come, including shipping's inclusion in the EU Emission Trading Scheme (EU ETS), would impose additional costs if producing emissions. Each tonne of heavy fuel oil (bunker fuel) consumed can produce approximately 3.2 tonnes of CO2 in exhaust gases if not captured. For example, large ships consuming 70 metric tonnes of bunker fuel would therefore be charged carbon levies on 224 metric tons of CO2 emitted. At $150 per tonne of CO2, with 250 sailing days per year, a ship operator would therefore see an additional charge of $8.4 million per year, or $250 millionover a 30-year lifecycle.

Nuclear powered marine solutions, however, may not be subject to the challenges and difficulties of sourcing, producing, storing, and burning carbon-based or other alternative fuels identified above while generally supplying more power.

4. Advanced Nuclear Opportunities

To address the various international and national marine industry decarbonization challenges, the opportunities for nuclear power for marine applications merits consideration.

Here, the critical main criteria for advanced reactor technologies are presented which should be met for applications to be considered feasible solutions in the marine environment.

4.1. Key Criteria for Success

U.S. Congress defines advanced nuclear reactors in the Nuclear Energy Innovation Capabilities Act of 2017 (P.L. 115-248) as "a nuclear fission reactor with significant improvements over the most recent generation of nuclear fission reactors, which may include—

i. Inherent safety features
ii. Lower waste yields
iii. Greater fuel utilization
iv. Superior reliability
v. Increased resistance to proliferation
vi. Increased thermal efficiency, and
vii. The ability to integrate into electric and nonelectric applications"

With modern reactor advancements in fuel management, reactor safety, and manufacturing, advanced nuclear reactors can be feasible for use in marine applications and applied to supply alternative synthetic or e-fuels. However, certain criteria exist for applications in the marine environment that nuclear reactors must meet to be considered feasible solutions. Three main evaluation criteria for the appropriate reactor technologies are the following:

- High-efficiency fuels that mitigate nuclear proliferation and reduce nuclear waste
- Reactors that are passively safe with minimal licensing complexity
- Economic viability

The optimum solutions for advanced marine reactors are those which fulfil the three main criteria for success in the maritime industry.

1. Creating an acceptable security and risk profile for a maritime reactor would be based on excellent fuel efficiency and long fuel cycles where few or no reactor refuelling activities are required. With no fresh fuel replenishment and no spent fuel discharge during the life of a marine asset, the security, safeguarding and proliferation risks should be reduced.

2. Inherent safety is essential for maritime nuclear reactors. This means the implementation of passive safety systems and reactor designs that make operations, management, and emergency planning feasible and approachable for commercial maritime reactor applications. For example, any reactor design which can minimize the Emergency Planning Zones (EPZ) will reduce liability for operators.

3. Modern designs for small, advanced reactors would be the preferred installations on marine assets due to their limited size and weight. To reduce cost, small, advanced reactors may be manufactured in optimized arrangements in dedicated facilities or specialist shipyards. This manufacturing concept may be an opportunity to diverge from conventional nuclear building techniques for the purpose of developing competitive nuclear solutions for marine decarbonization.

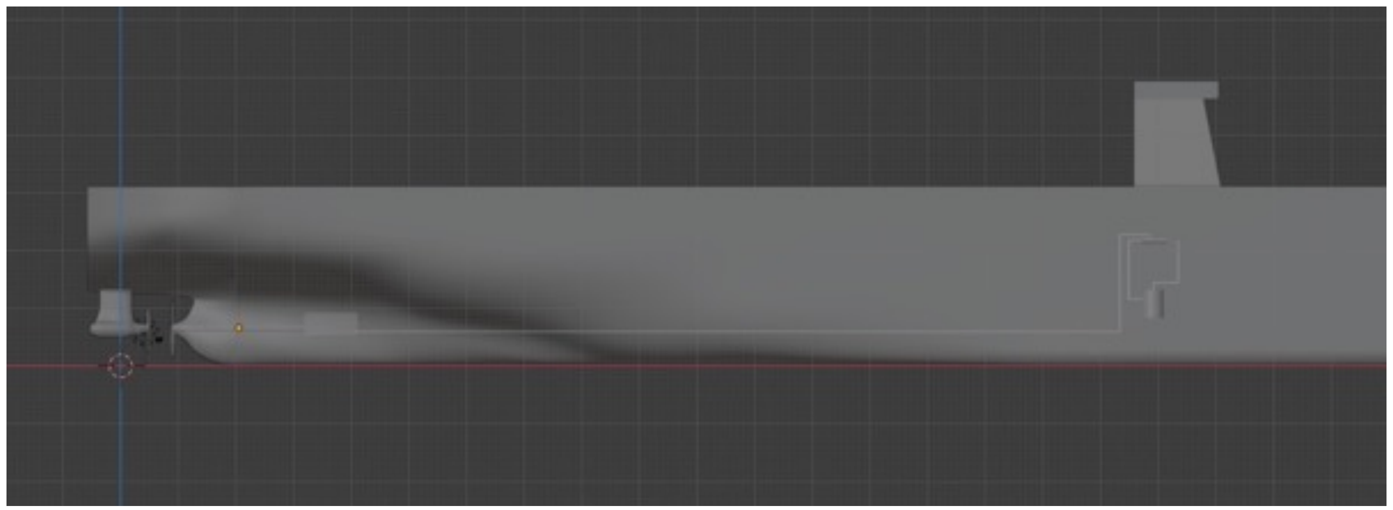


Figure 28: Concept design study of nuclear-electric powered container ship – courtesy CORE POWER

4.2. Conventional Marine Nuclear Reactors

Today, over 160 ships (mostly naval), are powered by more than 200 small nuclear reactors. Some 700 nuclear reactors have been used in ships since the 1950s.

Naval reactors are uniformly conventional pressurised water reactor (PWR) designs that differ from commercial land-based reactors. PWRs were originally designed to power propulsion for nuclear submarines and were used in the original design (1957) of the United States' first commercial power plant at Shippingport Atomic Power Station, which was also the world's first full-scale atomic electric power plant devoted exclusively to peaceful use.

Naval PWRs deliver enormous power from a very small core and therefore most run on highly-enriched uranium.

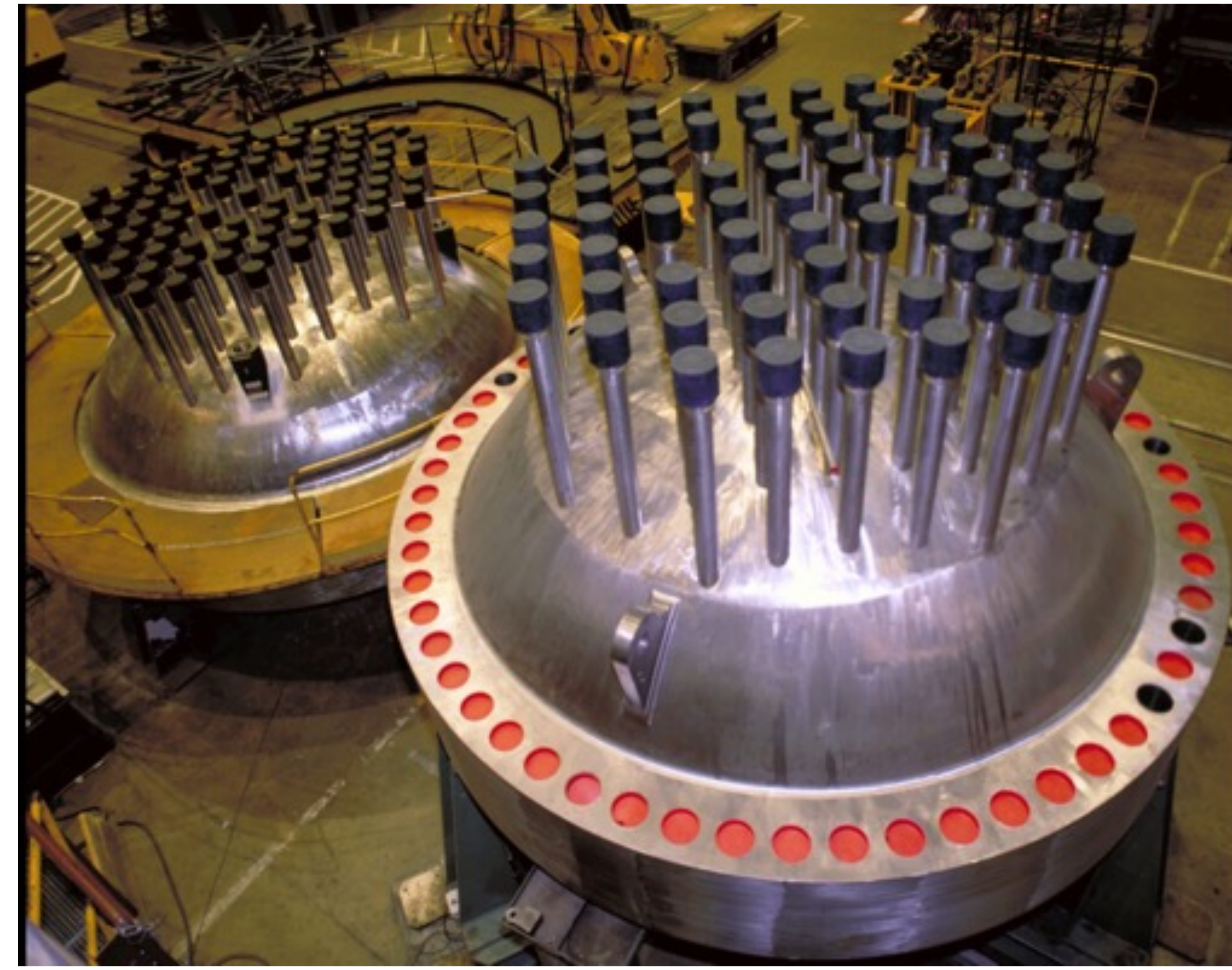


Figure 29: Nuclear Regulatory Commission image of pressurized water reactor vessel heads (Image: Wikipedia)

A simplified figure of the PWR reactor and supporting systems is shown in Figure 30. The PWR works by circulating its light water 'coolant' (as liquid, at ~300° C) through a pressurised 'primary loop' that passes through a steam generator, transferring heat to a 'secondary system' that produces steam to either produce electricity or drive a propeller shaft. The water enters through the bottom of the reactor's core at about 548 K (275° C; 527° F) and is heated as it flows upwards through the reactor core to a temperature of about 588K (315° C; 599° F). The water remains liquid despite the high temperature due to the high pressure in the primary coolant loop, usually around 155 bar.

Pressure in the primary circuit for light water 'coolant' is maintained by a pressurizer, a separate vessel that is connected to the primary circuit and partially filled with water which is heated to the boiling point for the desired pressure using submerged electrical heaters. To achieve a pressure of 155 bars, the pressurizer temperature is maintained at 345° C (653° F), which causes a difference between the pressurizer temperature and the highest temperature in the reactor core of 30° C.

Since the coolant water must be highly pressurized to remain liquid at high temperatures, a PWR requires high strength piping and a heavy pressure vessel that increases construction costs. Additional high-pressure components such as reactor coolant pumps, pressurizer, and steam generators are also needed. The higher pressure can increase the consequences of a radiological accident.

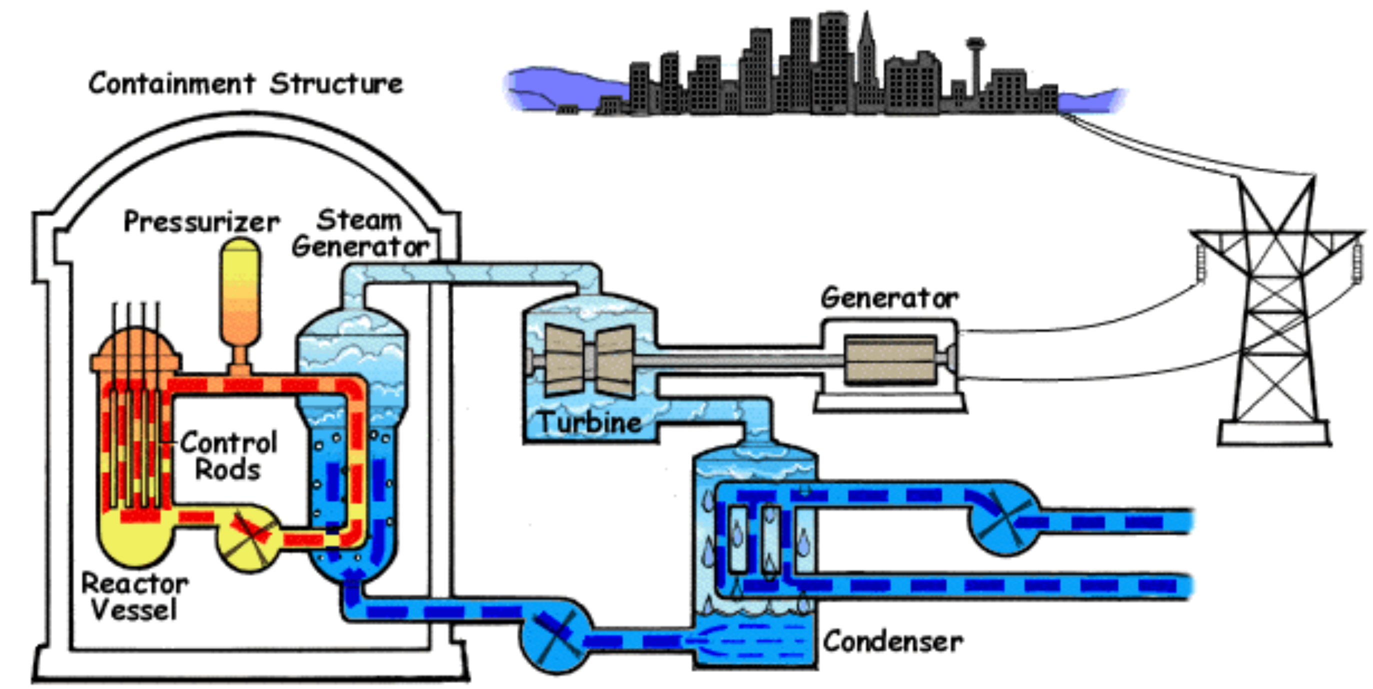


Figure 30: Pressurized Water Reactor, NRC

The first nuclear-powered submarine, the USS Nautilus, put to sea in 1955. Nuclear power revolutionized the U.S. Navy and the technology was shared with Britain. The U.S. Navy has accumulated more than 5,400 reactor-years without incident. Special envoy John Kerry reflected on his career with nuclear propulsion at COP26 saying the U.S. Navy had 'never had a spill, never lost a crew member' due to a nuclear event onboard. Nuclear power at sea has proven to be one of the safest and most efficient ways to power large ships with the benefit of zero emissions.

A submarine reactor is required to withstand the shock and vibration experienced by all warships in active service due to ocean turbulence and enemy action. The U.S., British, and Russian navies rely on steam turbine direct propulsion while French and Chinese submarines use their turbines to generate electricity for propulsion power.

4.3. Emergency Planning Zones

All nuclear plants, regardless of size and design, require an emergency planning zone (EPZ) around the reactor. As most reactors today are pressurized (including boiling light water reactors and gas cooled reactors), the EPZ must consider the formation of a plume of airborne radioactive contamination that would form if pressure was released from the reactor into the surrounding environment. As a result, EPZ requirements for commercialized power reactors are large.

In the U.S., for example, The Nuclear Regulatory Commission requires two emergency planning zones around a nuclear plant, shown in Figure 31.

The first zone is a Plume Exposure Pathway EPZ extending about 10 miles in radius around the reactor site. Protective action plans within this area are designed to avoid or reduce dose from potential exposures such as inhaling radioactive particles.

The second is an Ingestion Exposure Pathway EPZ extending about 50 miles in radius around the reactor site. Protective action plans for this area are designed to avoid or reduce dose from eating or drinking radioactive materials.

Following the Three Mile Island accident in 1979, these two EPZs were included to establish standards upon which emergency plans are to be reviewed. As the size requirements for the two EPZs were derived from conservative analyses for large light water reactors, the 1980 rulemaking contemplated that the size of the EPZs can be determined on a case-by-case basis for gas-cooled reactor designs and for reactors with a power level less than 250 MW thermal. For these plants where the NRC grants an exemption to the regulations, smaller EPZs will be permitted due to their reduced risk.

(https://www.nei.org/news/2018/nrc-staff-agrees-smrs-wont-need-large-epzs)

Therefore, advanced reactors may potentially have very small EPZs. For example, ships powered by PWRs require an EPZ that is usually larger than the dock of the port of call and sometimes larger than the port itself. This would be an obstacle for conventional nuclear-powered ships calling in commercial civilian ports, while a well contained, properly shielded reactor using an advanced design residing below the waterline could potentially achieve an EPZ which would not expend beyond the boundaries of the hull, making regular port calls and waterways transits a possibility.

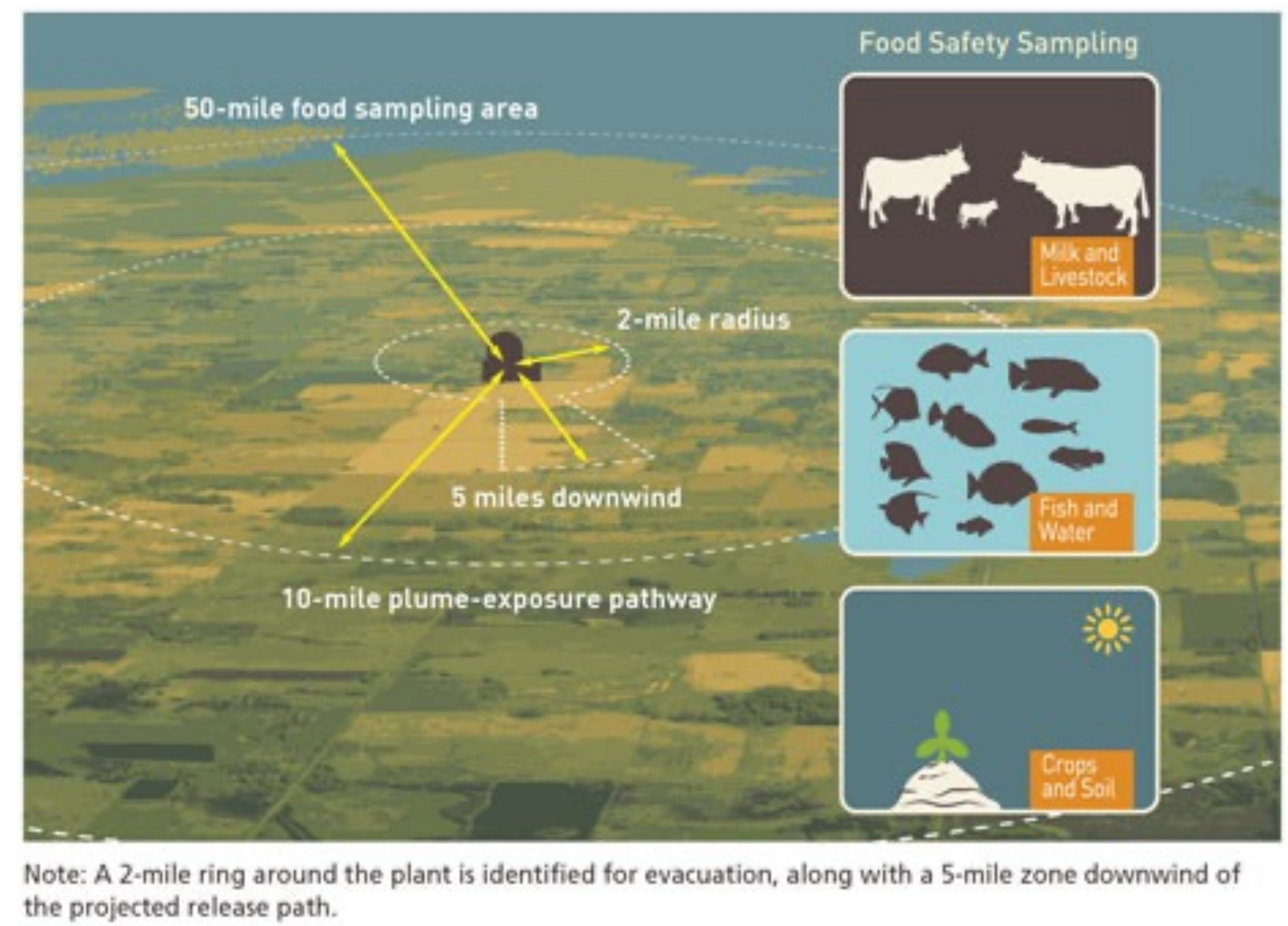


Figure 31: Emergency Planning Zones around Nuclear Facilities

5. Maritime Opportunities

The maritime industry must consider transitioning towards low-emission and zero-emission energy sources to decarbonize shipping. This includes considering nuclear energy to generate propulsion power or produce offshore energy.

When considering the global fleet and history of nuclear navies, an opportunity for nuclear ship propulsion could be sought where the reactor technology, installation and performance are sufficiently distinguished from naval reactors to be allowed in a U.S. flagged fleet of civilian ships. New reactor designs could offer feasible solutions for integrated nuclear electric power systems on large ships which are fuelled for life, carrying more cargo, sailing for longer, while remaining economically competitive.

Ships powered by advanced nuclear solutions could provide enough durable, clean power for large ships to sail for 30 years, and with the proper infrastructure, to provide clean electric power to ports and remote shoreside communities as temporary floating nuclear power plants.

Other maritime opportunities for advanced nuclear applications include deploying marine reactors for electric power and industrial heat power production, as well as the offshore production of zero-carbon green fuels, water desalination or other industrial applications.

5.1. Lower Capital Costs

Reactors at sea could allow for large capital cost reductions compared to land-based nuclear plants due to simpler, smaller designs and the potential to take advantage of the modular construction techniques used in shipyards. By moving from unique, expensive, and large-scale production to mass-manufactured modular reactors, it may be possible to achieve significant cost savings through economies of volume.

5.2. Benefits of Nuclear Propulsion

Various benefits of nuclear-powered propulsion can be realized depending on the power requirement of vessels and their operating conditions.

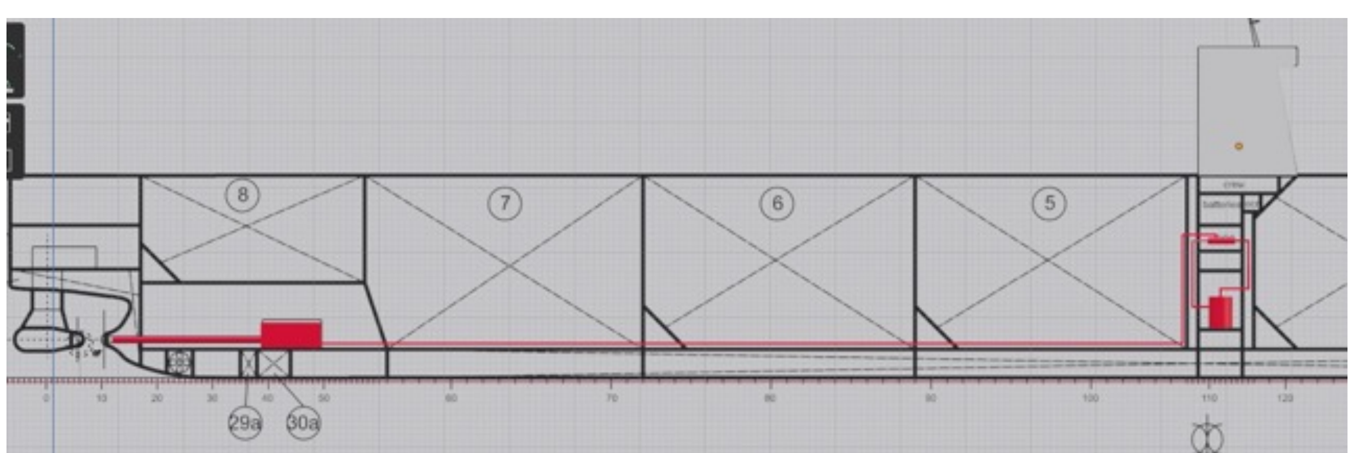


Figure 32: Concept design study of nuclear-electric powered container ship – courtesy CORE POWER

It is expected that installing nuclear reactors on ships will require some modification from conventional ship design. The heat cycle from the reactors can generate useful heat and produce onboard electricity from turbines. This could facilitate the complete electrification of large vessels, eliminating the need for shaftlines to the propeller. Instead, prime movers (motors) consume onboard electricity to generate mechanical power drive propellers and thrusters or other equipment. Electrical losses along power distribution cables would be compensated by increased output from the reactor.

Due to the weight of small reactors, while designed to be smaller and safer than conventional reactors on ships, loading them onto a ship or offshore installation may present challenges for stability and structural capability. Like large engines, the small reactors would likely be located low in the floating structure to maximize stability and supported appropriately with foundational structures. Some nuclear ship designs locate the reactor at midships, or mid-length, of the vessel, to optimize longitudinal loads on the hull structure. This is acceptable in comparison to conventional vessel design with aft located engine rooms because shaftlines are not required.

Figure 33: Concept design of a large bulk carrier powered by a molten salt reactor – Courtesy CORE POWER

5.3. A Trans-Atlantic alliance between U.S. and U.K.

The U.S. and the U.K. have a long history of maritime, naval, and nuclear collaboration. The recent AUKUS trilateral security pact between Australia, the U.K., and the U.S. which was announced on 15 September 2021 for the Indo-Pacific region, under which the U.S. and the U.K. will help Australia to acquire nuclear-powered submarines, demonstrates just how close the two allies are in sharing technology, information, and strategic responsibilities.

The U.K. has one of the world's most illustrious maritime histories, while the U.S. has nuclear experience of equal standing. In the U.S., the regulation of naval reactors is delegated to the Navy and the Department of Energy (DOE) through the National Nuclear Security Administration (NNSA), where the commander of the Nuclear Navy serves as deputy.

In the U.K., regulation of the Royal Navy reactor fleet is also delegated to the Navy. The U.K. Department for Transport (DfT) 'Maritime 2050' policy, which was published in 2019, set out clear ambitions for the U.K. to use Brexit as a catalyst to strengthen their maritime industries. While ambitious, it requires a set of prime drivers to succeed.

A resurgent U.K. maritime sector may not be achieved by competing on price alone and needs unique new technologies. Under a public consultation to the U.K. Maritime and Coastguard Agency in October 2021, 50 leading shipping companies made the case for a new generation of advanced nuclear technologies to be applied to floating power and nuclear propulsion as the key competitive driver that could achieve the majority of the policy items in ‘Maritime 2050’.

One opportunity to demonstrate maritime applications for advanced nuclear may lie with the U.S. sharing the responsibility to regulate and inspect advanced nuclear ships with the U.K., which has equally mature nuclear and maritime regulators.

The opportunity for a home-flagged fleet of nuclear ships exists under the U.S. and U.K.’s rigorous technical policies and security regulations and serve as a model to the world of how nuclear maritime applications can be deployed with international collaboration.

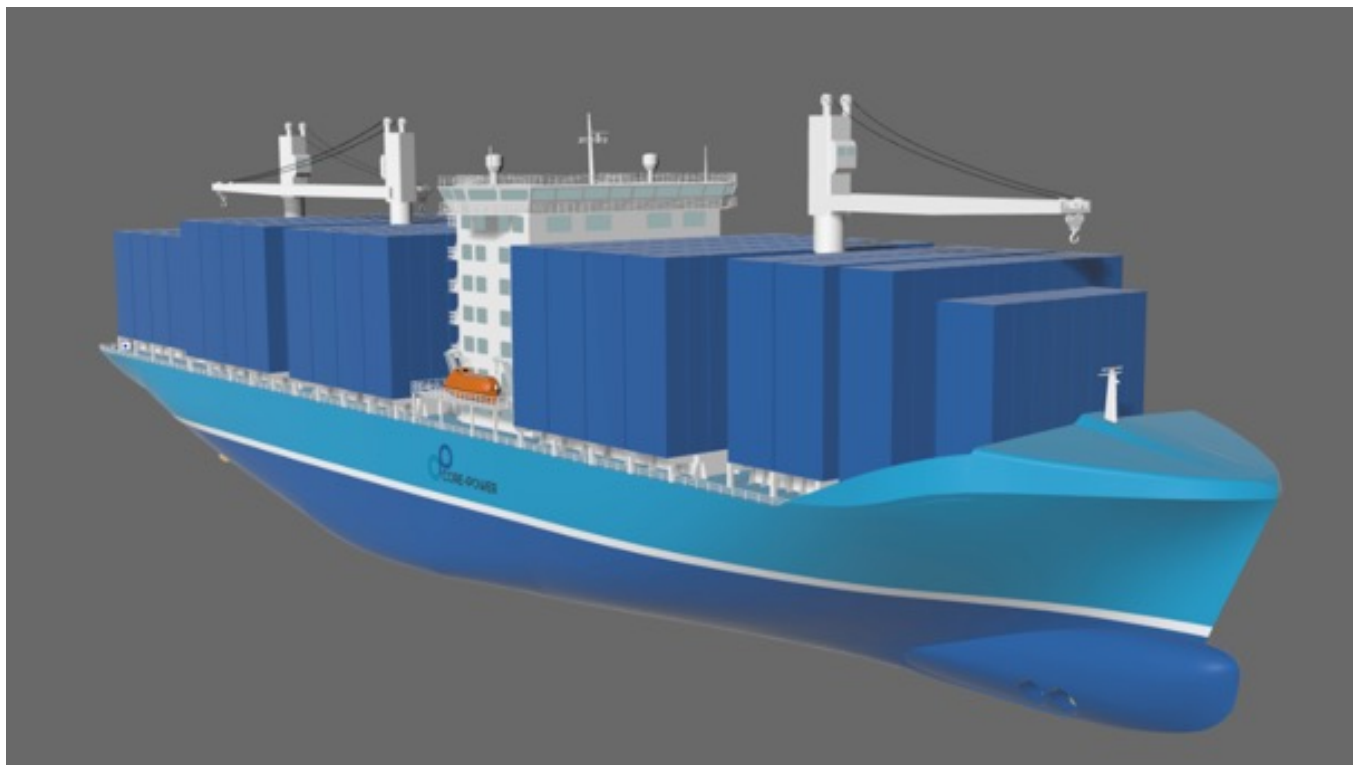


Figure 34: Concept design of a small containership powered by the HPR – Courtesy CORE POWER

5.4. Benefits of Offshore Nuclear Installations

Where nuclear powered commercial ships have many possible applications, they may experience challenges when establishing an approved trade route between ports or nations due to nuclear policy in those locations. However, stationary or temporary nuclear installations offshore may not be subject to trade route requirements or port entry restrictions. These applications are considered for sustainable decarbonization of the marine industry and to address land-based energy needs.

5.4.1. Producing Decarbonized Fuels

This section explores the example of floating nuclear reactor to support the production of offshore green e-fuels.

As the market for alternative marine fuels grows, the industry may benefit from the development of green electro-fuels combining reliable, clean electricity with high temperature heat for efficient hydrogen production. These designs could be supported by modern infrastructure and energy funding opportunities, for example the U.S. Department of Energy’s Hydrogen Program Request for Information (RFI) (Q1 2022).

The representative example for the application of offshore nuclear power is the production of ammonia from hydrogen generated from nuclear power. This may be especially attractive in areas where space on land or land-based infrastructure is limited. The production of ammonia from hydrogen involves converting water and air into a carbon-free fuel or feedstock for chemical manufacturing and industrial processes including fertilizer production. An offshore installation or platform fitted with these production facilities powered by an advanced nuclear reactor could act as ammonia bunkering points to support a sustainably decarbonized ammonia supply chain.

The proposed facility described below is an offshore floating power plant, housing the reactor and the power conversion system. The offshore plant would output a mix of electricity and heat.

The plant design includes an offshore ammonia production facility and storage tanks. These types of facilities could build upon the design and operational experience of the oil and gas industry.

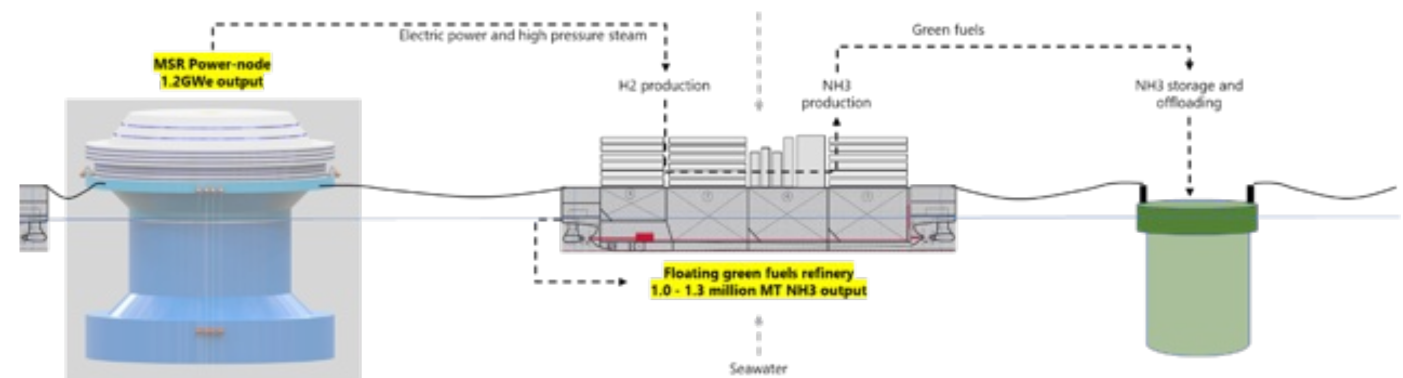


Figure 35: Schematic of complete nuclear powered production plant for 1 million metric tons green ammonia

Current plans for the provision of zero-carbon ammonia rely on relatively new carbon capture technologies used to sequester CO2 from the ‘steam methane reforming’ process where hydrogen is split from natural gas. Other plans take advantage of low-cost renewable electricity, although the scalability of this arrangement has yet to be proven.

The decarbonization of other difficult-to-abate sectors such as chemical and steel manufacturing as well as aviation can increase demand for the manufacture of zero carbon fuels.

6. Regulatory landscape

6.1. A New Challenge

Nuclear regulators and licensors are in the process of developing rules and frameworks to license a new generation of advanced reactors. Conversely, there is currently little progress in regulating advanced reactors in the maritime domain. Regulators are primarily focused on land-based nuclear reactor applications within their own jurisdictions.

Every country has its own nuclear regulations and laws. Many countries are signatories to international nuclear third-party Conventions. The Conventions and National laws are not typically technology focused but are designed so all Contracting Parties have laws and regulations in place confirming to the legal regime for civil liability for nuclear damage provided for in the Conventions.

Applications for maritime reactors, on the other hand, would operate in a dynamic ocean environment and likely would require a new set of local, national, or even international licensing rules to allow different design solutions to be deployed in various locations.

6.2. Components of the Current Framework

A major consideration for current nuclear regulatory frameworks involves the safe operations using nuclear fuel and reactors while in international waters, nearshore, or in ports. This means that to verify these operations in a secure manner, there will need to be renewed focus on common international regulatory security standards.

Figure 36: The International Maritime Organization (IMO) in session.

Due to complexities of port requirements, political sensitivities, safety, and security case requirements, nuclear powered merchant ships will likely only be able to visit certain ports and transit certain sea routes.

For example, at the current time the Suez Canal authority strongly discourages the transit of nuclear powered merchant ships and the carriage of nuclear fuel due to accident and security concerns. (https://www.maritime-executive.com/editorials/could-a-nuclear-powered-cargo-ship-transit-the-suez-canal) Occasionally, military nuclear powered ships or submarines transit the Suez and Panama canals under agreement with the local authorities. Theoretically, a vessel powering arrangement could allow a reactor to be deactivated prior to a canal transit and an auxiliary electrical power plant could be used to maintain power.

The most common international treaty covering merchant nuclear-propelled ships is the United Nations' Convention of the Law of the Sea (UNCLOS). This is supported by both the International Maritime Organization (IMO) convention for the Safety of Life at Sea (SOLAS) – initially established after the 1912 Titanic disaster, and the IMO Convention on the Liability of Operators of Nuclear Ships and Code of Safety for Nuclear Ships (which, when written, was focused on the use of marine PWRs only). General provisions for nuclear ships are listed in SOLAS Chapter VIII and detailed provisions in IMO Resolution A.491(XII). Each of these would require modernization to include advanced nuclear reactor technologies.

The International Atomic Energy Agency (IAEA) related manuals and regulations include:

- Safety regulations for the Transport of Radioactive Material (2018 edition) – (STI/PUB/1798 ¦ 978-92-0-107917-6)
- Security of Radioactive Material in Transport – (STI/PUB/1872 ¦ 978-92-0-105119-6)
- Security of Nuclear material in transport – (STI/PUB/1686 ¦ 978-92-0-102015-4)

Figure 37: The International Atomic Energy Agency in session.

The IAEA publication Nuclear Security Recommendation on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225), is intended to provide guidance to States and their competent authorities on how to develop or enhance, implement and maintain a physical protection regime for nuclear material and nuclear facilities, through the establishment or improvement of their capabilities to implement legislative and regulatory programmes.

There is nothing within IAEA publications specific to the operational security, security design requirements, or standards required of commercial nuclear-powered ships. However, there may be an opportunity to consider how or if the IAEA INFCRIC/225 (STI/PUB/1481 ¦ 978-92-0-111110-4) principles could be adapted, adopted, and applied to nuclear-powered commercial ship design.

There is currently no internationally recognised legislation that applies to commercial nuclear ships.

The U.K. Government is bringing forward new legislation in the form of the Merchant Shipping (Nuclear Ships) Regulations 2021. This is recently under consultation through the IMO and remains undated. It will be applicable to all U.K.-flagged nuclear merchant ships worldwide and all nuclear merchant ships in U.K. waters.

For any international security framework or regulation to be truly effective, it must encompass both the nuclear-powered ships and the waters or ports into which they intend to travel.

Consideration has been given to an assessment of the regulatory readiness for nuclear ships including consideration of the readiness of the primary nuclear regulator e.g., U.K.'s ONR/MCA, U.S.' USCG/DOE/NRC, IAEA, IMO, Classification Rules, and insurance.

To achieve deployment of nuclear-powered merchant ships, it is important for international collaboration to accelerate both advanced reactor development and deployment projects.

There are already efforts in Europe and the U.S. to commercialize advanced modular reactor technologies for transport and industry.

The 'Transport Safety Standards Committee' (TRANSSC) in the Division of Radiation, Transport, and Waste Safety of the International Atomic Energy Agency (IAEA) has established a working group on Transportable Nuclear Power Plants (TNPP) which is reviewing work scope to develop a framework both for fuelled reactors fitted on maritime offshore assets, and as propulsion units on ships. In a parallel effort, the IAEA Division of Nuclear Installation Safety is considering development of a technical document on the safety, security and regulation of TNPPs. The technical document may assist countries in developing national safety standards and in achieving agreement on an international framework that allows for multilateral approval of international TNPP transportation without compromising nuclear security goals.

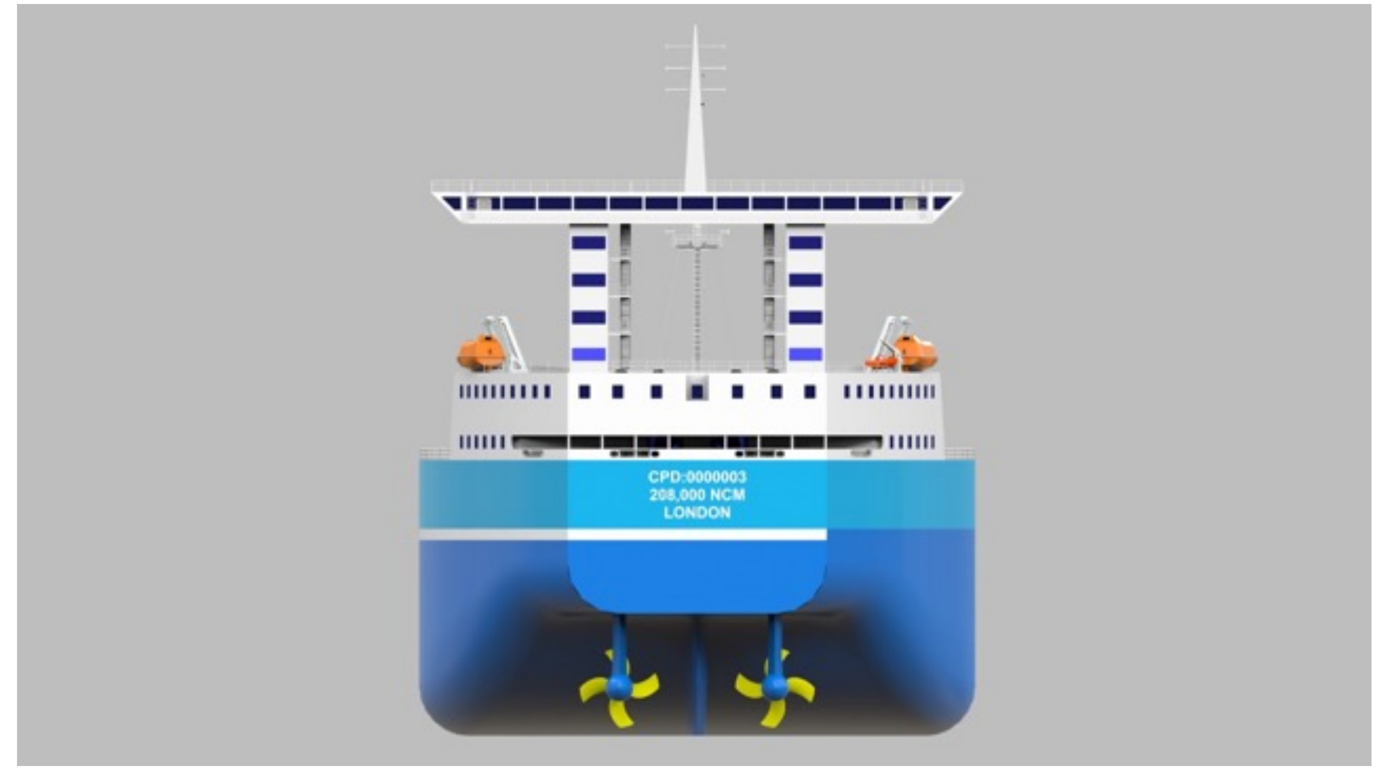


Figure 38: Concept design of a nuclear-electric Capesize bulk carrier – Courtesy CORE POWER.

Advanced nuclear technologies for marine applications will require the consideration of international partners and action through both the IMO and IAEA. The efforts of the U.K. Maritime Coastguard Agency (UKMCA) to modernize SOLAS VIII (A.491.XII) are essential in this regard. The collaboration and coordination required between the UKMCA, the Office for Nuclear Regulation (ONR), and other relevant regulators in respect of national rules and the IAEA will play a vital role in making U.K. flagged nuclear-powered ships possible by 2030.

Before international agreement is achieved through IMO for a 'demonstrator ship', there will be a need for bi-lateral agreements with other jurisdictions. For example, agreement between the U.K. and U.S. or U.K. and Japan, where, for the jurisdictions of each party, there are already significant agreements for the use and transport of nuclear material.

The current International Code for the Safe Carriage of Packaged Irradiated Nuclear Fuel, Plutonium and High-Level Radioactive Wastes on Board Ships (INF Code) currently regulates the transport of radioactive material at sea. The INF code does offer a goals-based framework for ensuring the safe transport of radioactive material at sea and has been regularly updated and revised by the IMO since its first adoption.

There is also a need to consider international safeguard challenges with regards to nuclear technology in merchant nuclear powered ships including non-proliferation, material control and accounting (MC&A) and inspection.

Credible threats to merchant shipping today exist worldwide, ranging from potentially hostile states to motivated organizations with malicious intent (including pirates) who have both the capability (experience) and intent to attack and hold crews and ships at ransom. It can be assumed that this threat would also exist for nuclear powered merchant ships. Therefore, regulatory efforts will need to include establishing an international regulatory security routine / framework that seeks to mitigate the risks of such attacks.

6.3. IMO Code of Safety for Nuclear Merchant Ships

In the 1970s, the IMO developed the 'Code of Safety for Nuclear Merchant Ships', Resolution A.491.(XII) under the Safety of Life at Sea Convention Chapter VIII (SOLAS VIII) to cover the design, construction, operation, and decommissioning of civilian vessels powered by nuclear energy.

Regulation A.491(XII) as it was adopted considers only pressurized water type reactors where the steam-generating system is being used directly to power the drive shaft. These current regulations do not consider the progressive changes in reactor technology or electrification developments seen in the last several decades. The regulation would require revision to allow the deployment of next-generation small reactors in marine environments.

In August 2021, the United Kingdom Maritime Coastguard Agency (UKMCA), under the U.K. Department for Transport, which is the U.K.'s representative agency at the IMO, announced its intention to pass SOLAS VIII including the 'Nuclear Code' (Res. A.491XII) into law by the end of 2022. A call for consultation was sought from industry, regulatory agencies, and other relevant stakeholders. Specifically, the UKMCA sought inputs on the likelihood of nuclear-powered ships being deployed under the U.K. flag within an appraisal period running up to 2030.

6.4. Convention on the Liability of Operators of Nuclear-Powered Ships (1962)

The convention on the liability of operators of nuclear-powered ships, sometimes known as the "Brussels Convention", is a document produced by the IMO setting out the liability of nuclear vessel operators in the event of an accidental release of material or accident. The convention was never ratified by the IMO. However, its proposed rules are in accordance with other international agreements on liability for nuclear reactors. The convention states that the operator of the nuclear vessel is fully accountable and responsible for maintaining relevant insurance in the case of nuclear damage. This convention is of particular relevance to the deployment of marine floating reactors as the "Vienna Convention on Civil Liability for Nuclear Damage" and the "Paris Convention on Third Part Liability in the Field of Nuclear Energy" specifically excludes reactors transported by means of sea or air. The ratification or updating of the Brussels Convention and implementation in International Law is therefore likely to be needed to allow the insuring of small modular reactors before they can be deployed.

6.5. IMO/IAEA Safety Recommendations on the Use of Ports by Nuclear Merchant Ships (ISM Code)

The International Safety Management (ISM) code focuses on a ships' safety management system when docked in port. This document was developed jointly between the IMO and IAEA and published in 1980. The document is likely to be updated to integrate changes in the best practices developed in the last 40 years to reduce nuclear risk.

6.6. International Atomic Energy Agency (IAEA) Conventions

While there has been no known work carried out by the IAEA on the use of small modular reactors for propulsion of maritime vessels, some regulatory work has been carried out in both anticipation and response to the developments in floating nuclear power stations. A comprehensive report was published in 2013, "Legal and Institutional Issues of Transportable Nuclear Power Plants – a Preliminary Study" (STI/PUB/1624 ¦ 978-92-0-144710-4).

This report sets out the framework under which floating plants will operate. It states that if a plant is transported in an unfuelled state, there is relatively little difference between these systems and conventional reactors. However, if the reactor is transported in a fuelled state, then there will be different considerations. The current IAEA guidance and treaties could be considered appropriate for the operation of maritime deployed SMR's with a mode of operation that involves them remaining static, however this will not be the case for nuclear-propelled vessels.

In order to be enforced by governments, the IAEA guidance would need to be adopted into a Convention or other agreement and national law. This may require engagement from the IAEA with Governments, the Organisation for Economic Co-operation and Development (OECD) and other regulators to align and make mandatory change to international regulations.

Ships operating as maritime transport will also have to abide by and be aware of local regulations. There are a wide variety of local regulations on nuclear. While some countries, especially those with existing nuclear fleets, already have developed regulations on the berthing of nuclear vessels, while other countries such as New Zealand do not allow nuclear-powered or nuclear-armed vessels to enter their national waters.

Due to the possible challenges related to national and international regulatory regimes, early designs may focus on local or national applications, for example, Jones Act Vessels in the U.S.

6.7. IAEA Regulations for the Safe Transport of Radioactive Material (SSR-6)

SSR-6 is the current standard that countries can apply through their national regulations to govern the transport of material both on land and at sea. The standards are primarily concerned with the movement of packaged nuclear material when transporting fuel or waste. SSR-6, as well as the INF code, give specifications for ships that are carrying nuclear material including specifications to ensure that crew members are not exposed to an adverse level of radiation as well as regulations on redundancy in communication and navigation systems. These are more specific than standard IMO guidance.

7. Environmental and Economic Impact

Wider economic benefits of nuclear-powered marine fleets could include an increase in activities related to ship design, shipbuilding, commercial and technical operations, insurance, standards development, and of course, training and certification of marine officers and crew.

Advanced reactor-powered ships could be faster, carry more cargo, and do so for longer than the current fleet is capable. Each ship's produced power may also be capable of powering port equipment when connected, such as loading and discharging gear. This type of effort may support local goals of decarbonizing ports and substantially improving the environment for the communities that live and work there.

Opportunities for stimulated economic growth in coastal communities may also be possible with new generations of vessels capable of competing with land-based transport options while reducing emissions and providing cheaper, more competitive transportation costs.

Further benefits may be realized with the possibility of combining existing and new power infrastructure with terrestrial and floating production of hydrogen and other derived decarbonized fuels.

7.1. Benefit to Ports

Providing decarbonized electricity to port facilities can allow for the decarbonization of port operations. This opportunity may be realized with offshore nuclear power stations supplying the local grid, or by visiting vessels connecting to the local grid and providing electricity (sometimes known as reverse cold-ironing).

Nuclear powered vessels in port may not require fuel bunkering, and further benefit ports by reducing congestion at bunkering locations.

With global trade expected to continue increasing and ports beginning to establish decarbonization plans, marinized advanced nuclear power could provide an ideal solution.

7.2. More Jobs and Seafarers

The introduction of nuclear-powered shipping could lead to a paradigm shift in the staffing and crewing of nuclear-powered vessels. Officers on nuclear-powered ships may require a higher degree of training than those trained to operate conventionally fuelled vessels.

This could be a new career path opportunity for both STEM college graduates and for veterans of the U.S. nuclear navy. In supporting the growth of the global fleet, it may not just be seafarer jobs that can be created.

For example, the technical development and registration of these vessels in any nation can create downstream jobs in nuclear fuelling, maintenance, insurance, brokering, and finance industries.

From a shipowner and operators' perspective, the move to advanced nuclear propulsion could see a fundamental shift in the way these vessels are managed and operated throughout their lifetime. For example, advanced nuclear vessels requiring no refuelling could offer substantially reduced operating expenditures (OPEX), helping to offset the expected higher capital expenditures (CAPEX) of reactor powered assets.

Removing volatility from the OPEX and cost of maritime propulsion would allow for longer, more economically predictable transportation contracts, which in turn would be easier for owners to finance.

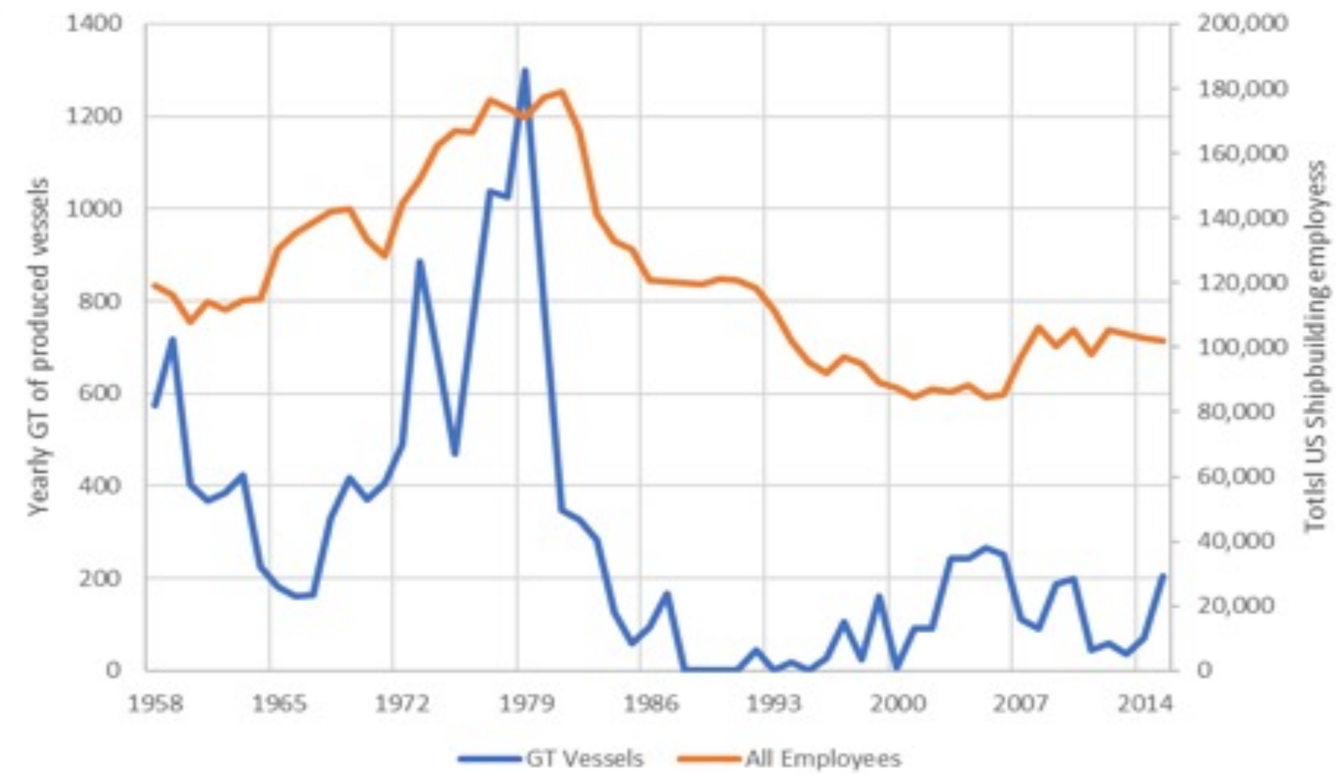


Figure 39: Summary of the GRT of commercial ships built yearly and the total number of employees engaged in the U.S. shipbuilding industry

7.3. Immunity to Carbon Levies

Advanced nuclear maritime applications could allow for zero-emission solutions and be resistant to carbon pricing related to anthropogenic emissions. One ton of heavy bunker fuel oil can produce up to 3.2 tons of emitted CO2.

The benefits of immunity to carbon levies can be illustrated in a simple example. Large ships consuming 70 metric tons of bunker fuel per day, or close to 500,000 tons over a lifetime, can emit more than 1.5 million tons of CO2 when in service. So, with a carbon levy of $200 per ton, for example, these ships could see an increased OPEX of $300 million over a vessel's lifecycle.

8. Conclusion

Increasing attention is being paid to global sustainable decarbonization for minimizing climate change and finding environmentally friendly future energy solutions. Current trends in population, energy, and trade show increasing demand for powering solutions that may stress currently available resources. Advanced nuclear power, with enhanced safety features and optimized functionalities, may offer a practical solution.

Specialized applications in the maritime industries are also looking for the best solution to meet decarbonization goals and energy requirements.

With advanced nuclear technologies considered as solutions to decarbonize and modernize commercial shipping and offshore industries, nuclear maritime demonstration projects can show the feasibility as well as the challenges of implementing widespread nuclear solutions for the maritime industry.

Floating reactors, whether to power floating production of green hydrogen or for ship propulsion, would operate in a dynamic environment and need to meet key criteria for success. These include asset safety, protection of nuclear fuel (i.e., non-proliferation), and economic viability.

Marine applications can also be challenged by the limits of current licensing and regulatory regimes. Licensing rules will need modernization to allow different designs to be tested, demonstrated, and deployed in marine environments and offshore locations.

There are many possible applications for nuclear power incorporated with maritime assets. Building on the experience of nuclear navies, marine vessel propulsion is the first application that comes to mind. However, international policy and regulations regarding the transport and movement of nuclear materials may create challenges at first for commercial (merchant) nuclear vessel demonstration and deployment.

The purpose of demonstration projects is to not only investigate the feasibility of nuclear technologies integrated with maritime systems, but also the feasibility of licensing and registering the nuclear application under new regimes. For this reason, demonstration projects should be supported by both technical and regulatory parties, such as the opportunity for the U.S. and the U.K. to combine technical and regulatory expertise in international demonstration activities. This opportunity for international collaboration of nuclear maritime demonstration projects is explored more in later Reports of this series.

This report aims to highlight the opportunities for nuclear-maritime applications and introduce the general challenges of the regulatory landscape as well as the environmental benefits and economic impacts that may occur.

The following reports in this series will focus more specifically on the regulatory landscape, advanced nuclear technologies, opportunities for demonstration projects, and the socioeconomic impacts of nuclear-maritime applications.

[i] Equasis , The 2020 World Merchant Fleet , 2020

[ii] The Great Lakes Seaway Partnership, Shipping on the Great Lakes-Seaway – Efficient. Green. Sustainable, 2018

[iii] Martin Associates, Economic Impacts of Maritime Shipping In The Great Lakes - St. Lawrence Region , 2018

[iv] US Army Corp of Engineers , 2019 - Mississippi River System , 2020

[v] HIS Markit , The River Barg Still Plays a Role in U.S Transportation , 2009

[vi] Man, Propulsion Trends in Bulk Carriers , 2015

9. Appendix A

Ship Types

9.1. Tankers

Tankers as a total fleet carry approximately 38% of the total bulk of cargoes. Tankers move approximately 2.0 billion metric tons of oil every year, second in efficiency only to pipelines. The average cost of the transport of crude oil by tankers amounts to U.S. $5 to $8 per cubic meter ($0.02 to $0.03 per US gallon).

In the United States Navy and Military Sealift Command, a tanker used to refuel other ships is called an oiler (or replenishment oiler if it can also supply dry stores) but many other navies use the terms tanker and replenishment tanker.

Oil spills can have devastating effects on the environment. Crude oil contains polycyclic aromatic hydrocarbons (PAHs) which are very difficult to clean up and can last for years in the sediment and marine environment.

Considering the volume of oil carried at sea, tanker owners' organizations argue that the industry's safety record is excellent, with only a tiny fraction of a percentage of oil cargoes being spilled. INTERTANKO (the International Association of Independent Tanker Owners) has observed that "accidental oil spills this decade have been at record low levels—one-third of the previous decade and one-tenth of the 1970s—at a time when oil transported has more than doubled since the mid-1980s."

The International Tanker Owners Pollution Federation has tracked almost 10,000 accidental spills that have occurred since 1974. Most spills result from routine operations such as loading cargo, discharging cargo, and taking on fuel oil. Of these 91% of the operational oil spills are small, resulting in less than 7 metric tons per spill.

Following the Exxon Valdez spill in 1989, the United States passed the OPA-90 (Oil Pollution Act of 1990), which disallowed single-hull tank vessels of 5,000 gross tons or more from U.S. waters from 2010 onward. Tankers were required to have double-hull construction to protect oil cargo from spilling in the cases of groundings or collisions.

Following other tanker incidents in Europe, the European Union passed stringent anti-pollution packages (known as Erika I, II, and III), which also require all tankers entering its waters to be double-hulled since 2010.

This tanker fleet is sub-divided into the following ship types.

Crude oil tankers are mostly large ships carrying raw commodity cargoes from oil fields to refineries. These are typically categorized by size, where Aframax vessels carry up to 100,000 tons of crude oil or dirty product, Suezmax vessels carry up to 160,000 tons, or 1 million barrels, and VLCCs (Very Large Crude Carriers) carry up to 320,000 tons or 2 million barrels of cargo. Even larger ships were built in the 1970s, but proved uneconomical.

Clean petroleum product tankers (CPP) are mostly medium-sized and smaller ships carrying refined oil products from refineries to consumer destinations, or on arbitrage routes. These include Handysize tankers carrying up to 35,000 tons of clean products like gasoline, jet fuel and naphtha. Due to their smaller size, Handysize or Intermediate tankers can access ports of all sizes. The largest clean tanker fleet is comprised of Medium Range tankers (MRs) capable of carrying between 35,000 and 45,000 tons (MR 1) and 45,000 to 55,0000 (MR 2) tons of product. The largest product tankers are called Long Range (LR) and can carry between 55,000 and 80,000 tons (LR 1) and between 80,000 and 160,000 tons (LR 2).

9.2. Gas Tankers

Gas tankers are classified by their carrying capacity of specific gases. In general, the most common gas cargo is LPG (liquified petroleum gas) extracted from petroleum reserves and LNG (liquified natural gas) extracted from hydrocarbon deposits near fossil fuels.

- Fully pressurized gas carrier are pressurized oceangoing LPG carriers with horizontal, cylindrical or spherical cargo tanks of between 20,000 and 90,000 cubic meters and overall lengths ranging from 140m to 229m.
- Semi-pressurized ships have cylindrical, spherical, or bi-lobed tanks carrying propane at a pressure of 8.3 bar (121 psi), and a temperature of 14 °F (−10 °C).
- Ethylene and gas/chemical carriers are more sophisticated tankers with cylindrical, insulated, stainless steel cargo tanks able to accommodate cargoes at temperatures ranging from a minimum of -155 °F (-104 °C) to a maximum of 176 °F (80 °C) and at a maximum tank pressure of 4 bar (58 psi).
- Fully refrigerated ships are built to carry liquefied gases at low temperature and atmospheric pressure between terminals equipped with fully refrigerated storage tanks ranging in capacity from 20,000 to 100,000 m3. LPG carriers in the 50,000–80,000 m3 size range are often referred to as VLGCs (Very Large Gas Carriers).
- Liquefied Natural Gas (LNG) carriers are mostly between 125,000 and 135,000 m3 in capacity. Recent introduction of several smaller ships of between 18,000 and 19,000 m3 built after 1994 to service the needs of smaller volume imports.
- Compressed Natural Gas (CNG carrier) are ships that rely on high pressure, typically over 250 bar (2900 psi), to increase the density of the gas and maximize the possible commercial payload.

9.3. Dry Bulk Ships

A dry bulk carrier or bulker is a ship specially designed to transport unpackaged bulk cargo, such as grain, coal, ore (major bulks) or bauxite, building materials, sand etc. (minor bulks) in its cargo holds.

Bulk carriers make up 21% of the world's merchant fleets and range in size from single-hold mini-bulk carriers to huge ore-ships able to carry as much as 400,000 metric tons of cargo. 82% of all bulkers in the global fleet were built in Asia.

Bulkers are classified by their cargo-carrying capacity or deadweight tons (dwt) as well as whether or not the ship can self-load aiguished in

- Geared bulkers are those fitted with cargo cranes and equipment for self-loading and unloading.

- Small geared bulkers up to 20,000 dwt are mostly used for short sea, coastal, and river transportation of all bulk commodities.
- Handysize bulkers are typically sized up to 45,000 dwt, fitted typically with 4 cargo cranes. These 'Handies' are often fitted with deck stanchions used in the log trade to carry lumber loaded in both the holds and on deck.
- Supramax and Ultramax vessels are larger versions of the Handysize bulker and can carry up to 65,000 tons of cargo. These are the workhorses of the minor bulk trade as they are relatively small and flexible enough to sail on large rivers and into remote or underdeveloped ports.
- Gearless bulkers do not have cranes fitted onboard and rely on shore gear or port operations for loading and unloading.
- For longer distance transportation of major bulk commodities like grain, coal, and iron ore, most larger ships rely on shore-gear for port operations and do not have cranes fitted onboard for loading and unloading. The use of ships with larger cargo carrying capacity gives global commodity traders the economy of scale required to move vast quantities of energy, food, and minerals from producing regions to the consumer regions, efficiently and at low cost.
- The biggest segment of the gearless fleet is the Panamax segment which consists of ships between 65,000 and 100,000 dwt. Panamaxes are the largest bulkers able to transit the Panama Canal locks, restricted by the length and width (beam) of a ship. Over 3,500 Panamax bulkers sail the globe and a vibrant futures market exists for the price of using these ships.

Over the last 30 years, the emergence of China as a major industrial economy and the rapid expansion of the Chinese fixed asset investment sector through buildings and infrastructure has led to a huge steel industry requiring a reliable feedstock of high-quality iron ore. The main iron ore extracting regions are found on the Australian and South American continent and require ever large quantities of iron ore transport. This has led to the emergence of a dominant fleet of the largest bulk carriers known as Capesize and VLOC (Very Large Ore Carriers). Over 1,600 'Capes' now regularly haul over 1 billion tons of iron ore every year to steel producers. Capesize vessels are too large to transit the Suez Canal and must route around South Africa's Cape of Good Hope. These can carry up to 210,000 tons of cargo whilst VLOCs can carry up to 400,000 tons.

9.4. Container Ships

A container ship also known as a boxship is a cargo ship that carries all of its load in truck-size intermodal containers, in a technique called containerization. Container ships now as much as 90% of oceangoing non-bulk cargo. Container ship capacity is measured in twenty-foot equivalent units (TEU) where 40-foot (2-TEU) ISO-standard containers is predominant.

The largest modern container ships can carry up to 24,000 TEU and container ships now rival crude oil tankers and bulk carriers as the largest commercial ocean going vessels.

Containerization has lowered shipping costs and decreased shipping time, which in turn has spurred growth of international trade. Containerization has revolutionized manufacturing by allowing on time guaranteed delivery and just in time delivery systems.

Containers are delivered to the docks by road, rail or a combination of both for loading onto container ships using cranes, installed either on the pier or on the ship, which are used to place containers on board the ship. When the hull has been fully loaded, additional containers are stacked on the deck.

There are 7 main categories of containership, ordered by their carrying capacity in twenty-foot-equivalent boxes.

As of 2019, the Port of Shanghai in China was the world's busiest container port, with 43 million TEU handled. Seven of the busiest ten container ports are Shanghai in 1st place, Ningbo 3rd, Shenzhen 4th, Guangzhou 5th, Qingdao 7th, Hong Kong 8th and Tianjin 9th. Other container ports include Singapore at 2nd, Busan in South Korea at 6th and Rotterdam in the Netherlands in the 10th position.

Container trade flows within Asia reached an estimated volume of 41.5 million TEUs in 2021. Trade flows from the Far East to North America and Europe amounted to some 23.6 million TEUs and 14.7 million TEUs in 2021, respectively. The global container trade is forecast to grow at a compound annual growth rate of 3.9 % between 2022 and 2025.

Table 8: Capacities of Types of Containerships

Containership category	Capacity - TEU
Ultra Large Container Vessel (ULCV)	14,501 and more
Neopanamax	10,000–14,500
Post-Panamax	5,101–10,000
Panamax	3,001–5,100
Feedermax	2,001–3,000
Feeder	1,001–2,000
Small feeder	Up to 1,000

9.5. Passenger Ships

A passenger ship is a merchant ship whose primary function is to carry passengers on the sea. While typically passenger ships are part of the merchant marine, passenger ships have also been used as troopships and often are commissioned as naval ships when used as for that purpose.

Passenger ships include ferries, ocean liners and cruise ships. Ferries move passengers and vehicles (whether road or rail) over various lengths of water. Ocean liners are typically passenger or passenger-cargo vessels transporting passengers and often cargo on longer line voyages. Cruise ships often transport passengers on round-trips, in which the trip itself and the attractions of the ship and ports visited are the principal draw.

Because of changes in historic and international measurement systems, it is difficult to make meaningful and accurate comparisons of ship sizes. Historically, gross register tonnage (GRT) was a measure of the internal volume of certain enclosed areas of a ship divided into "tons" equivalent to 100 cubic feet (2.8 m3) of space. Gross tonnage (GT) is a comparatively new measure, adopted in 1982 to replace GRT. It is calculated based on "the moulded volume of all enclosed spaces of the ship", and is used to determine things such as a ship's manning regulations, safety rules, registration fees, and port dues.

GT does not distinguish between mechanical and passenger spaces, and thus is not directly comparable to historic GRT measurements. Gross tonnage is promoted as the most important measure of size for passenger vessels, as the ratio of gross tonnage per passenger – the Passenger/Space Ratio – gives a sense of the spaciousness of a ship, an important consideration in cruise liners where the onboard amenities are of high importance.

This reflects the much lower relative weight of enclosed space in the comparatively light superstructure of a ship versus its heavily reinforced and machinery-laden hull space, as cruise ships have grown slab-sided vertically from their maximum beam to accommodate more passengers within a given hull size.

9.6. Other Ships

Ro-Ro Vessels are named for their roll-on, roll-off capability to load cars and trucks, either for vehicle transport or as a part of a ferry service. They are distinguished by one or more ramps for vehicle loading. Other types of vehicle carriers include:

- Ro-Lo: roll-on, roll-off vessels equipped with cargo access for loading and unloading
- PCC: Pure Car Carriers intended for the transport of new automobiles to location of final sale
- PCTC: Pure Car/Truck Carriers are a more modern term for PCCs fitted with specific carrying capabilities for trucks.

OSVs are Offshore Service Vessels which generally serve offshore installations or activities related to offshore oil & gas exploration and exploitation. They serve a variety of purposes including delivering fuel and provisions supplies, crew transport, anchor handling, buoy management, towing, and even icebreaking activities around offshore structures.

Icebreakers are often multi-purpose vessels with the key feature of strengthened and specially shaped bows designed for breaking through sea or lake ice up to several meters deep. Icebreaking ships dedicated to clearing shipping routes through ice covered areas are often run by coast guard administrations or naval forces to protect those routes and the ships that pass through them. Many OSVs that serve offshore installations in cold latitudes are often fitted with icebreaking capability. Research vessels may be capable of icebreaking if they operate or carry out research activities in polar regions, for example the USCG Polar Star or the RRS Sir David Attenborough. Some large yachts are also designed with icebreaking capability.

Due to the high power requirements needed for icebreaking operations, large power plants are installed onboard. For this reason, the Russian icebreaker fleet is fitted with nuclear power to provide sufficient thrust to power through some of the thickest sea ice formations in the world. Russia's State Atomic Energy Corporation Rosatom operates their icebreaker fleet and use only pressurized water reactors with enriched uranium fuel.

Research Vessels are also multi-purpose vessels and commonly owned by national entities for research and sea exploration. Many research vessels are involved in relatively small, coastal operations for scientific expeditions and data collection. Larger vessels are engaged in long voyages and are away from their home port for months at a time. Due to the variety of scientific equipment onboard and activities carried out, research vessels are often fitted with additional power for scientific loads.