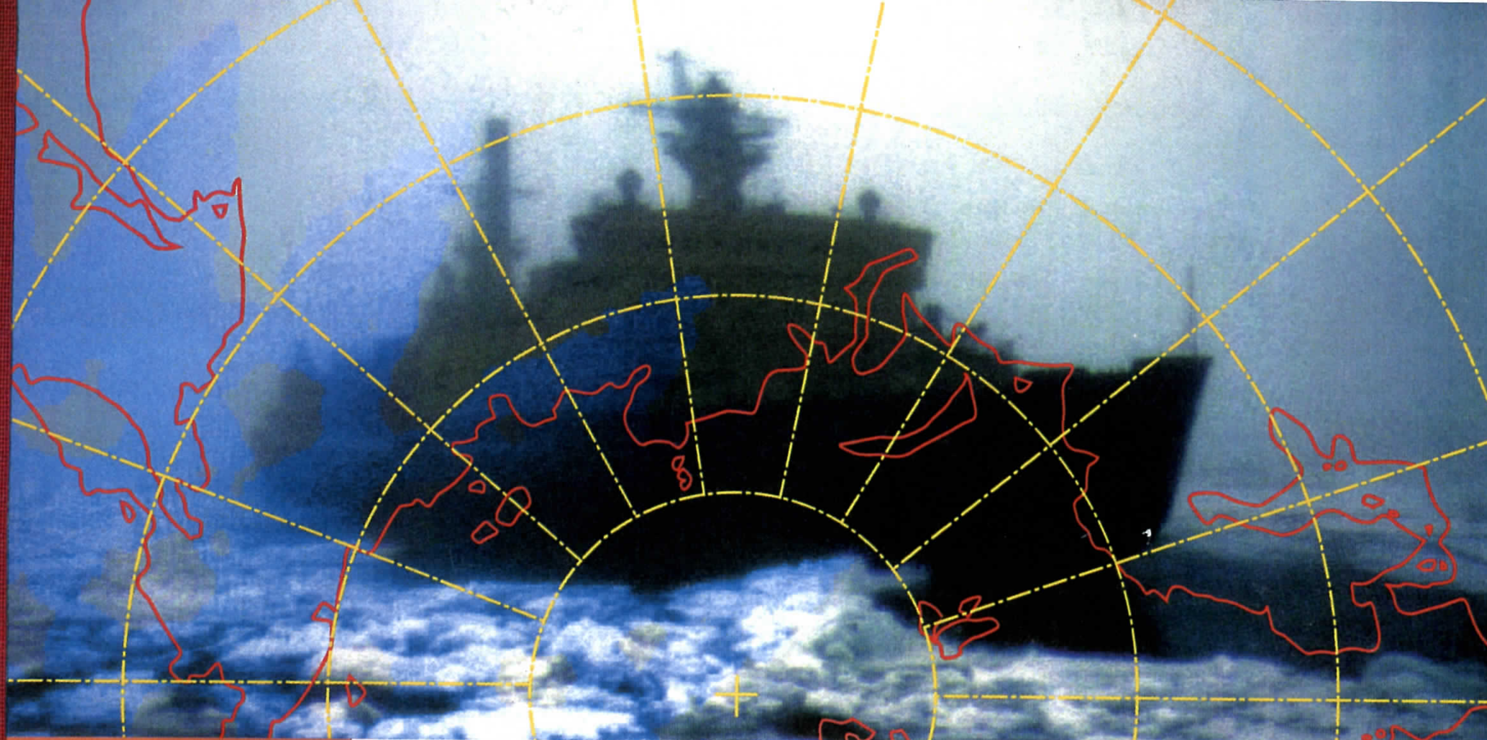

INSROP WORKING PAPER
NO. 73 - 1996, III.07.6

The Potential of the NSR with a Nuclear Icebreaking Container Ship

By Tomoji Takamasa,
Koichi Kondo, Kunio Miyashita,
Shogo Hayashi and Izuo Aya

INSROP International Northern Sea Route Programme

Central Marine Research & Design Institute, Russia

The Fridtjof Nansen Institute, Norway

Ship and Ocean Foundation, Japan

International Northern Sea Route Programme (INSROP)

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Sub-programme III: Trade and Commercial Shipping Aspects

Project III.07.6: The Potential of the NSR with a Nuclear Icebreaking Container Ship

Supervisor: Tomoji Takamasa

Title: **The Potential of the NSR with a Nuclear Icebreaking Container Ship**

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FOREWORD - INSROP WORKING PAPER

INSROP is a five-year multidisciplinary and multilateral research programme, the main phase of which commenced in June 1993. The three principal cooperating partners are **Central Marine Research & Design Institute (CNIIMF)**, St. Petersburg, Russia; **Ship and Ocean Foundation (SOF)**, Tokyo, Japan; and **Fridtjof Nansen Institute (FNI)**, Lysaker, Norway. The INSROP Secretariat is shared between CNIIMF and FNI and is located at FNI.

INSROP is split into four main projects: 1) Natural Conditions and Ice Navigation; 2) Environmental Factors; 3) Trade and Commercial Shipping Aspects of the NSR; and 4) Political, Legal and Strategic Factors. The aim of INSROP is to build up a knowledge base adequate to provide a foundation for long-term planning and decision-making by state agencies as well as private companies etc., for purposes of promoting rational decisionmaking concerning the use of the Northern Sea Route for transit and regional development.

INSROP is a direct result of the normalization of the international situation and the Murmansk initiatives of the former Soviet Union in 1987, when the readiness of the USSR to open the NSR for international shipping was officially declared. The Murmansk Initiatives enabled the continuation, expansion and intensification of traditional collaboration between the states in the Arctic, including safety and efficiency of shipping. Russia, being the successor state to the USSR, supports the Murmansk Initiatives. The initiatives stimulated contact and cooperation between CNIIMF and FNI in 1988 and resulted in a pilot study of the NSR in 1991. In 1992 SOF entered INSROP as a third partner on an equal basis with CNIIMF and FNI.

The complete series of publications may be obtained from the Fridtjof Nansen Institute.

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III.07.6
The Potential of the NSR with a Nuclear Icebreaking Container Ship

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Contents

Abstract

Trade between Europe and the Far East using nuclear container ships is feasible in the near future. In terms of existing Russian nuclear icebreakers and cargo ships, the nuclear vessels have an advantage over conventional NSR ships with respect to the energy supply problem, i.e., the balance of loading fuel and its power output, -- or in other words, the energy intensity. This advantage may broaden the NSR utility period on the basis of its economic potential. Shipping expenses and the requirements of shippers will also justify the extension of the NSR season. Our study is a comparison of the operating and voyage expenses of a model nuclear container ship and conventional diesel ships. A nuclear icebreaking container ship is now being designed by the Shipbuilding Research Association of Japan. Research and development of an advanced marine reactor (Marine Reactor X: MRX) for an icebreaker, which may possibly be installed in the near future, has been done by the Japan Atomic Energy Research Institute (JAERI). The MRX employs an integral pressurized water reactor (PWR), an in-vessel type control rod driving mechanism, a water-filled containment vessel, and a passive decay heat removal system that uses natural circulation. As a result, drastic improvements in safety and dramatic reductions in size and weight have been achieved. A cost comparison between the model nuclear icebreaking container ship and conventional diesel ships has been made that focuses on the advantages and disadvantages of the different transportation systems and the benefits and demerits for operators and shippers. Factors considered were the operating expenses and voyage expenses born by operators, and the freight, premium, interest, storage expenses, and sales opportunity costs paid by shippers. Using the above factors, the economic potential of a nuclear ship as an NSR merchant ship was examined as follows :

(1) A comparison was made of the ship-operating and container shipping expenses of the model nuclear icebreaking container ship sailing through the NSR and similar expenses of the high-speed diesel container ships passing through the Suez Canal.

(2) A comparison was made of the ship-operating and container shipping expenses of the model nuclear icebreaking container ship and similar expenses of a conventional diesel ship, both sailing through the NSR.

(3) A study was conducted to determine the kinds of cargo that could be carried economically by using a nuclear icebreaking container ship sailing through the NSR.

Our study shows that transporting cargo with a nuclear icebreaking container ship sailing through the NSR is economically feasible in comparison to existing container shipping and air transport.

Nomenclature

B : breadth, m

Cb : block coefficient, dimensionless

D : depth, m

d : draft, m

DW : dead-weight capacity, ton

DF : increase of freight, dollars

DT : shortening of transportation period, days

F : freight, dollars

f : freight of commodity: freight costs, dollars/freight ton

GT : gross tonnage, ton

I : premium, dollars

i : premium rate, dimensionless

I_P : insurance, dollars

Loa : length overall, m

Lpp : length between perpendiculars, m

LW : light weight, ton

M : building period, months

N : repayment period, years

n : ship's age, years

O : sales opportunity costs, dollars

P : construction costs (dept), millions of dollars

P_O : actual construction costs, millions of dollars

p' : limit value, dollars/freight ton

p : value of the commodity, dollars/freight ton

q : annual volume of commodity carried, TEU

R : interest, dimensionless

R_s : interest or cost of capital for the storage period, dollars

R_t : interest or cost of capital for the transportation period, dollars

r : inflation rate, dimensionless

r_s : interest for the storage period, dimensionless

r_t : interest for the transportation period, dimensionless

S : storage expenses, dollars

SHP : shaft horsepower, PS

T : transportation period, days

T_0 : period to the loss the value of commodity, days

W_t : thermal output, MWt

Y : ship's life, year

Greek symbol

α : stock-shipment ratio, dimensionless

1. Introduction

Many people have cherished the dream of developing a service between Europe and the Far East plying the Arctic Ocean ever since long-haul voyages started hundreds of years ago. Until recently, however, due to the regulations of the Union of Soviet Socialist Republics, foreign vessels were unable to navigate the Northern Sea Route (NSR) [1] along the Russian coast. But in 1990, Russia decided to relax those regulations, and in 1991, this route was opened to foreign vessels. Now, the International Northern Sea Route Programme (INSROP) has been implemented through the cooperation of the neighboring countries such as Russia, Norway, and Japan. They have been studying the possibility of using the NSR as a passage for transporting cargo on a year-round basis. Apart from the question whether the year-round service will be feasible or not, we have to determine what kinds of vessels could navigate the NSR as merchant ships. Although such research has been conducted greatly by the INSROP, we have especially examined the possibility of a nuclear icebreaking container ship sailing through the NSR in this study.

In recent years, industrial and economic globalization have developed remarkably. The task of container ships playing main roles in the world ocean carriage has become more important, and the demand for container ships has tended to increase along with the increasing "containerization" of cargo. While the size of container ships becomes larger for fulfilling the effective transport of increasing cargo volume, the container shipping, as a part of the intermodal transportation system which is combined with land carriage, is forced to keep severe regularity in the transport cargo. To facilitate such service, the trend in container-ship design is toward higher speeds. If a container service route between Europe and the Far East sailing through the NSR could be made viable economically, it bears great benefits from a global logistic viewpoint. The output of container ships is required to be larger, reflecting the demand for higher-speed and larger-size, however, the diesel engine which is popular for its low fuel cost, will not be the best choice with regard to energy supply, i.e., the balance of loading fuel and its power output or in other words the energy intensity. Nuclear power has the excellent advantage that a small volume of fuel can generate substantial power for a long period, and such an advantage cannot be found in the conventional power alternatives. Furthermore, the diesel engine entails an additional environmental cost due to the emission control regulation, as the International Maritime Organization (IMO) is recently studying the restriction and reduction of emissions of SO_X, NO_X and CO_2. Nuclear power, which emits no SO_X, NO_X or CO_2, can be an ideal candidate for future marine-engine power supply, and it gives us clean energy. In Russia, six nuclear icebreakers now sail the Arctic Ocean. Under the leadership of the Murmansk Shipping Company, Russia is also investigating the possibility of securing high-latitude transportation routes in all seasons, which would greatly shorten the sailing distance between Europe and the Pacific Ocean by building a large nuclear icebreaker [2]. In the light of these circumstances, the nuclear icebreaking container ship was isolated in this study and its economical potential as a NSR merchant ship has been examined and evaluated according to the following procedures.

(1) A comparison of the ship-operating and container shipping expenses of the nuclear icebreaking container ship sailing through the NSR and the high-speed diesel container ships passing through the Suez Canal.

(2) A comparison of the ship-operating and container shipping expenses of the nuclear icebreaking container ship and the conventional diesel ship, both sailing through the NSR.

(3) A study and definition of the characteristics of cargo that could be carried economically by using the nuclear icebreaking container ship sailing through the NSR.

2. Research and Development of Nuclear Ships

2.1 Current states of nuclear ships

· Warships with nuclear arms have been built and put into service by the U.S.A., Russia, England, France, and China. The world first development of nonmilitary nuclear ships started in 1955, and several development projects of nuclear ships were announced successively by Russia, the U.S., Germany, and Japan. All nuclear ships that have ever been built and operated are shown in **Table 2.1**. Also other countries like Canada, Italy, Norway, Sweden, and Belgium have been involved in similar programmes, but none of them managed to build any nuclear ships for nonmilitary use. The military and nonmilitary nuclear ships built to date are as follows [3].

U.S.A.:

· The cargo-passenger ship "Savannah," which has a loop PWR, was in service during 1962-1970.

· In collaboration with Germany, the design and construction of the integral- type reactor "EFDR" for the ore carrier "Otto Hahn" was carried out.

· The U.S. currently has 125 nuclear warships, with 19 others being built and two more in the planning stage.

· Design and research into nonmilitary nuclear ships were carried out with regard to container ships (1968), tankers (1969-1970), LNG tankers (1975), icebreaking tankers (1977), LNG submarine tankers (1981) and submarine tankers (1977).

· Research and development of integral-type reactor "CNSG- , CNSG- ,CNSG- , CNSG- and CNSG-100" was carried out, but none has been put to commercial use.

Russia:

· Eight nuclear ships have been built since the icebreaker "Lenin" went into operation in 1959. Currently, seven of those ships are operating, and one is decommissioned; Another is being built. All the reactors are semi-integral PWR type.

· The transport lighter/containership "Sevmorput," which has a semi- integral PWR, has been in service since 1988.

· There are 162 nuclear-armed warships operating, another nine being built.

· Integral PWR is now being researched.

Germany:

· The ore carrier "Otto Hahn," with an integral PWR, was in service during 1968-1979.

· Several types of integral PWRs were designed and developed, but no significant activity has

Table 2.1 Nuclear ships in the world

Ship's name		Lenin	Savannah	Otto Hahn	Mutsu	Arktika	Sibiri	Russia	Sevmorput	Taymyr	Soviet Soyuz	Vaygach	Yamal	Ural
Flag		Russia	U.S.A.	Germany	Japan	Russia	Russia	Russia	Russia	Russia	Russia	Russia	Russia	Russia
Kind of ship		Icebreaker	Cargo-passenger ship	Ore carrier	Test ship	Icebreaker	Icebreaker	Icebreaker	Transport lighter /containership	Icebreaker	Icebreaker	Icebreaker	Icebreaker	Icebreaker
Completion		Trial Sept. 1959	Aug. 1962	Nov. 1968	Feb. 1991	Nov. 1974	Oct. 1977	Dec. 1985	Dec. 1988	First critical Jun.1989	Dec. 1989	Jul. 1990	Jun. 1992	1994 (planning)
Loa/Lpp	m	134.0 / 124.0	181.5 / 166.1	171.8 / 157.0	130.0 / 116.0	147.9 / 136.0	147.9 / 136.0	150.0 / 136.0	260.3 / -	151.8 / -	150.0 / 136.0	151.8 / -	150.0 / 136.0	159.6 / 145.6
Bmax/Bwl	m	27.6 / 26.8	23.8 / -	23.4 / -	19.0 / -	29.9 / 28.0	29.9 / 28.0	30.0 / 28.0	32.2 / -	29.2 / -	30.0 / 28.0	29.2 / -	30.0 / 28.0	30.0 / 28.0
D/d	m	16.1 / 10.5	15.2 / 8.99	14.5 / 9.2	13.2 / 6.9	17.2 / 11.0	17.2 / 11.0	17.2 / -	18.3 / 10.68	15.2 / 8.1	17.2 / -	15.2 / 8.1	17.2 / -	17.2 / -
Displacement	ton	17,810	22,170	25,950	10,400	20,905	21,120	22,920	61,000	20,000	22,920	20,000	23,400	25,800
Maximum speed at calm sea	knot	19.6	20.2	16.0	17.5	20.8	20.8	20.8	20.0	18.5	20.8	18.5	20.8	-
Icebreaking ability	m	1.5	-	-	-	2.2~2.3	2.2~2.3	2.4~2.5	1.0	1.7~1.8	2.4~2.5	1.7~1.8	2.4~2.5	2.6~2.7
Shaft horsepower	PS	Center 19,600×1 Side 9,800×2	22,000×1	10,000×1	10,000×1	Maximum 24,000×3	Maximum 24,000×3	Maximum 24,000×3	40,000 (CPP)	Maximum (triple shaft) 48,000	Maximum 24,000×3	Maximum (triple shaft) 48,000	24,000×3	24,000×3
Propulsion		DC Motor Word-Leonard system Center 2, Side 2×2	Steam turbine 1	Steam turbine 1	Steam turbine 1	DC Motor AC-R-DC system Center 2, Side 2X2	DC Motor AC-R-DC system Center 2, Side 2×2	DC Motor AC-R-DC system Center 2, Side 2×2	Steam turbine 1	DC Motor Cycloconverter system Center 1, Side 1×2	DC Motor AC-R-DC system Center 2, Side 2×2	DC Motor Cycloconverter system Center 1, Side 1×2	DC Motor AC-R-DC system Center 2, Side 2×2	DC Motor AC-R-DC system Center 2, Side 2×2
Reactor type		PWR (Semi-Integral)	PWR (Loop)	PWR (Integral)	PWR (Loop)	PWR (Semi-Integral)	PWR (Semi-Integral)	PWR (Semi-Integral)	PWR (Semi-Integral)	PWR (Semi-Integral)	PWR (Semi-Integral)	PWR (Semi-Integral)	PWR (Semi-Integral)	PWR (Semi-Integral)
Thermal output	MWt	90×2	80×1	38×1	36×1	150×2	150×2	150×2	135×1	171×1	150×2	171×1	150×2	150×2
Main propulsion turbo generator	kWe (PS)	8,100×4 (11,000×4)	-	-	-	27,600×2 (37,500×2)	27,600×2 (37,500×2)	27,600×2 (37,500×2)	-	18,400×2 (25,000×2)	27,600×2 (37,500×2)	18,400×2 (25,000×2)	27,600×2 (37,500×2)	27,600×2 (37,500×2)
Main trubo generator	kWe	1,000×5	1,500×2	450×2	800×2	2,000×5	2,000×5	2,000×5	1,700×2	2,000×2	2,000×5	2,000×2	2,000×5	2,000×5
Aux generator	kWe	1,000×2	750×2	450×2	720×2	1,000×1 200×2	1,000×1 200×2	1,000×1 200×2	600×2 200×2	2,360×3 200×2	1,000×1 200×2	2,360×3 200×2	1,000×1 200×2	1,000×1 200×2
Complement (Engine Part)	persons	170	120 (24)	60 (23)	58 (24)	130	130	130	76	104	130	104	130	-
Operating time	hr	107,000	-	65,700	3,532	91,000	78,000	32,000	5,000	4,000	1,000	-	-	-

been observed since then.

England:

- Nuclear merchant ships have been researched since 1956, and an integral PWR has been designed and developed.
- 16 nuclear warships are in operation, four are being built and six others are in the planning stage.

France:

- Research and development of an advanced marine reactor for a merchant ship based upon a military use land reactor was carried out.
- A semi-integral PWR for the applications in merchant ships, power and heat co-generation are being researched.
- There are 10 nuclear-armed warships operating, four are being built and two others are in the planning stage.

China:

- A marine reactor for military use is now being researched.
- Six nuclear warships are in operation.

Japan:

- The experiments for collecting the operational data were performed using the test ship "Mutsu" in 1991. "Mutsu" is to be converted to a diesel powered ship. The works related to the conversion have been started at Sekinehama Port which is her permanent mooring port.

Canada:

- The nuclear merchant submarine "SAGA-1" has been built and is in operation in collaboration with France.

Others:

- Research and development of marine reactors has been carried out by Belgium, Holland, and Italy.

2.2 Studies on advanced marine reactors

The Japan Atomic Energy Research Institute (JAERI) has been conducting research and development on an advanced marine reactor, with the ultimate aim of building one. In the case of a marine reactor, the requirements for output, loading conditions, and automation system of the operation are slightly different depending on the type of ship in which the marine reactor is installed. Current research and development is devoted to two types of advanced marine reactors: the large reactor Marine Reactor X (MRX); and the Deep-sea Reactor X

(DRX) for a deep-sea ship. These would be installed in an icebreaking observation ship and a deep-sea scientific research ship, both of which are expected to be the next Japanese nuclear ships [4]. The conceptual design has already been established for both the MRX and the DRX; in parallel, the development of the element technology such as the test for the passive safety technological basis, and the development of the element equipment such as the in-vessel type control rod driving mechanism has been conducted. Currently being collected are the hydrothermal data indispensable for detailed design, conducting the engineering studies including the demonstration of the reliability of the new concept and the performance of the operation and maintenance. **Figure 2.1** shows the conceptual scheme of the plant, and its principal particulars are as follows.

Reactor power	100 MWt
Reactor type	Integral PWR
Reactor coolant	
Operating pressure	12.0 MPa
Core inlet temperature	282.5°C
Core outlet temperature	297.5°C
Flow rate	4,500 ton/h
Core	
Equivalent diameter	1.49 m
Effective height	1.40 m
Number of fuel assemblies	19
Number of fuel rods/assembly	493
Fuel rod outlet diameter	9.5 mm
Fuel inventory	6.3 ton
U-235 concentration	4.3 % (without Gd)
	2.5 % (with Gd)
Average burn-up	23 GWd/ton
Fuel lifetime	8 years
Control rod driving mechanism	
Type	In-vessel type
Number of CRDMs	13

Advanced Marine Reactor MRX

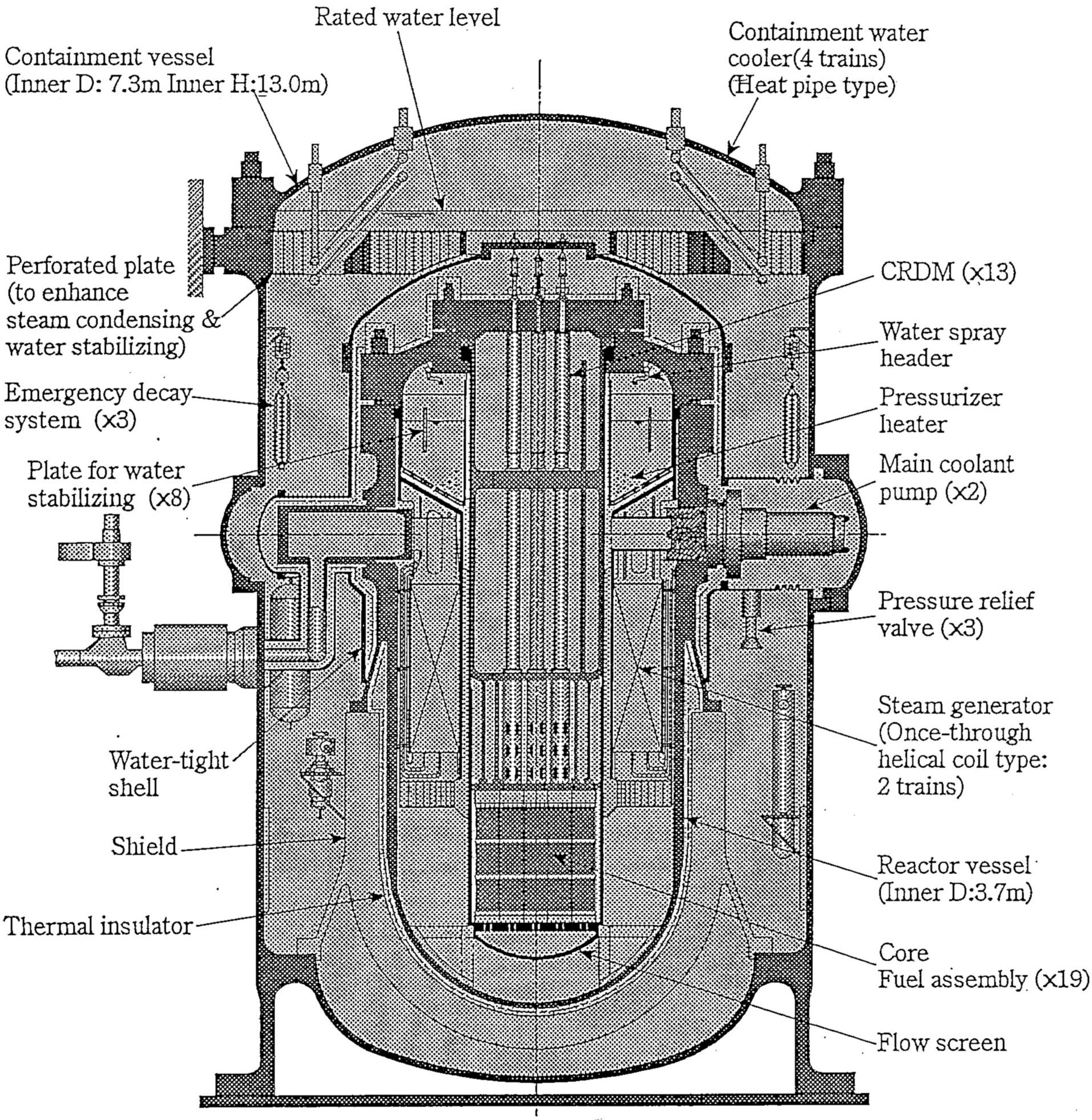


Figure 2.1 Conceptual schema of Marine Reactor X

Steam generator	
Type	Once-through helical coil
Tube material	Incoloy 800
Steam temperature	289°C
Steam pressure	4.0 MPa
Steam flow rate	168 ton/h
Containment vessel	
Type	Water-filled
Max. allowable pressure	4.0 MPa

The MRX is a marine reactor that can simultaneously achieve high safety, miniaturization and weight reduction by employing an integral PWR concept, an in-vessel type control rod driving mechanism, a water-filled containment vessel and a passive decay heat removal system by natural circulation. Although its output is roughly three times bigger than the one of "Mutsu," the containment capacity is roughly 0.7 times and the weight roughly 0.5 times smaller, whereby a drastic improvement in weight reduction and size-down can be achieved. Moreover the security characteristics as a plant is improved thanks to the passive decay heat removal system, even without an emergency core injection system.

2.3 The report on the cost evaluation of nuclear ships sailing the Pacific Ocean

JAERI has made a cost evaluation report on nuclear container ships with the MRX installed, sailing the North Pacific route [5]. Diesel container ships, whose speed is 18-24 knots and which carry 1,500-3,000 TEU (20-foot container equivalent unit), are dominant. As the size of container ships has become larger to transport a large volume of cargo, recent container ships often have a capacity of over 6,000 TEU. Nuclear power can deal with high power for the kind of large, high-speed vessel anticipated in the near future.

The cost evaluation report focused on whether the high-speed, large container ship with the MRX, with a varying number of containers (4,000/6,000/8,000 TEU) and ship's speed (25/30/34 knots), can economically compete with the diesel ships. The principal factors of the diesel and nuclear ship models for the calculation are shown in **Table 2.2** and **Table 2.3**, and one example of the said nuclear container ship models (6,000 TEU/30 knots) is shown in **Fig. 2.2**. The economic comparison was made with the required freight rate (RFR). The RFR is the transportation cost borne by the operator during the ship's life. The RFR for one container ship was calculated by adding together all the container shipping expenses such as capital costs, operating expenses, voyage expenses and decommissioning fee for a nuclear-powered ship, and then dividing this total by the number of TEU carried during the ship's life, assuming that the ship would be placed into service in 2015 and the life would be 20 years. The RFR is often utilized as the cost evaluation factor for the analysis and evaluation of the economy of a merchant ship. It is calculated from all the incurred shipping expenses divided by the number of TEU carried throughout the ship's whole life and this is the transportation cost of one TEU.

Figure 2.3 shows the calculation results of the RFRs in relation to the ship's speed. In ships with the same number of payload containers, the RFRs of the nuclear ships are higher than those of the diesel ships when the ship's speed is 25 knots. But this RFRs relation is inverse when the ship's speed becomes 30 knots. The more the ship's speed increases, the more nuclear ships become favorable. In terms of the payload capacity of containers, the larger the ships become, the lower the RFRs generally become. But the declining rate of RFRs in the case between 6,000 TEU and 8,000 TEU is much smaller compared to the case between 4,000 TEU and 6,000 TEU. This means that economics of scale are limited when the payload capacity of containers is over 6,000 TEU. Eventually, there are diseconomics of scale such as the difficulties in the management of assignment and cargo booking etc.. Comparing the RFRs of diesel container ships and the nuclear ships operated on the Pacific Ocean, it is found that the latter has an advantage over the former when the ship's speed is over 30 knots.

2.4 Technological research on the NSR

The "Pilot Project Report" [6] published by the Fridtjof Nansen Institute of Norway presents technological and economic research on the NSR. The problems pointed out in this report are described as follows.

1) Sea route: The NSR along the Russian coast, a sailing distance of 3,200 miles, is a route between the Atlantic Ocean and the Pacific Ocean through the Barents Sea, Kara Sea, Laptev Sea, East Siberian Sea, and Chukchi Sea (see **Fig. 2.4**). There are some shallow waters in this sea route such as the 10.1-13.0 meters depth in the Sannikova Channel and 6.7-8.0 meters depth in the Lapteva Channel, therefore there is a limit to the size of cargo ships able to navigate the NSR, which is 20,000 DWT (dead weight tonnage).

2) Sailing distance: **Table 2.4** shows the sailing distance of the different routes between Hamburg and the Far East or North American west coast, using the NSR and the conventional routes like the one through the Suez Canal. When using the NSR to transport goods to Yokohama, the sailing distance is about 40 percent shorter, and it is about 20 percent shorter

Table 2.2 Principal factors of high-speed diesel container ships

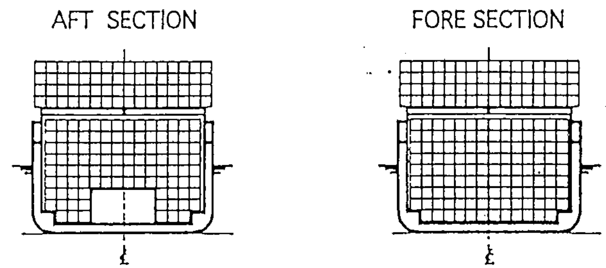
Type	Diesel								
Number of containers (TEU)	4,000			6,000			8,000		
Ship's speed (knot)	25.0	30.0	34.0	25.0	30.0	34.2	25.0	30.0	33.5
Lpp (m)	245.0	247.0	255.0	326.0	329.0	342.0	357.0	366.0	371.0
B (m)	40.0	40.0	40.0	40.0	40.0	40.0	42.5	42.5	42.5
D (m)	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5
d (m)	12.2	12.9	14.0	13.8	14.3	14.9	15.2	15.5	16.1
Cb	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
Displacement (ton)	70,400	75,400	84,200	105,800	111,000	120,300	135,700	142,700	149,500
GT (ton)	59,600	59,100	59,400	76,300	76,000	77,900	85,700	87,200	87,000
DW (ton)	48,400	49,500	52,400	70,400	71,800	74,400	92,600	94,400	96,500
LW (ton)	22,000	25,900	31,800	35,400	39,200	45,900	43,100	48,300	53,000
SHP (PS)	60,300	140,000	280,000	75,800	151,800	280,000	88,100	171,000	280,00
Thermal output (MWt)	—	—	—	—	—	—	—	—	—
Number of shafts	1	2	4	2	3	4	2	3	4

Table 2.3 Principal factors of high-speed nuclear container ships

Type	Nuclear								
Number of containers (TEU)	4,000			6,000			8,000		
Ship's speed (knot)	25.0	30.0	34.0	25.0	30.0	34.2	25.0	30.0	33.5
Lpp (m)	251.0	259.0	260.0	340.0	344.0	349.0	369.0	381.0	385.0
B (m)	40.0	40.0	40.0	40.0	40.0	40.0	42.5	42.5	42.5
D (m)	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5
d (m)	12.3	12.6	13.5	13.7	14.0	14.5	14.9	15.2	15.6
Cb	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
Displacement (ton)	72,500	77,100	82,500	109,500	113,300	119,300	138,100	144,900	150,100
GT (ton)	60,900	62,400	61,300	79,700	80,1000	80,300	89,300	91,500	91,500
DW (ton)	47,200	46,000	45,700	68,900	67,800	67,700	89,700	89,700	89,700
LW (ton)	25,300	31,100	36,800	40,600	45,500	51,600	48,400	55,200	60,400
SHP (PS)	54,600	125,300	242,700	69,200	135,700	246,600	79,800	152,800	247,600
Thermal output (MWt)	—	—	—	—	—	—	—	—	—
Number of shafts	1	2	4	2	3	4	2	3	4

PRINCIPAL FACTORS

Lpp	344.0m
B	40.0m
D	23.5m
d	14.0m
DW	67,800 ton
Number of containers	6,000TEU
Ship's speed	30knots
Type of engine	
Steam turbine × 3 set	
SHP	135,700PS
Reactor	
MRX × 2 set	
Thermal output	348MWt



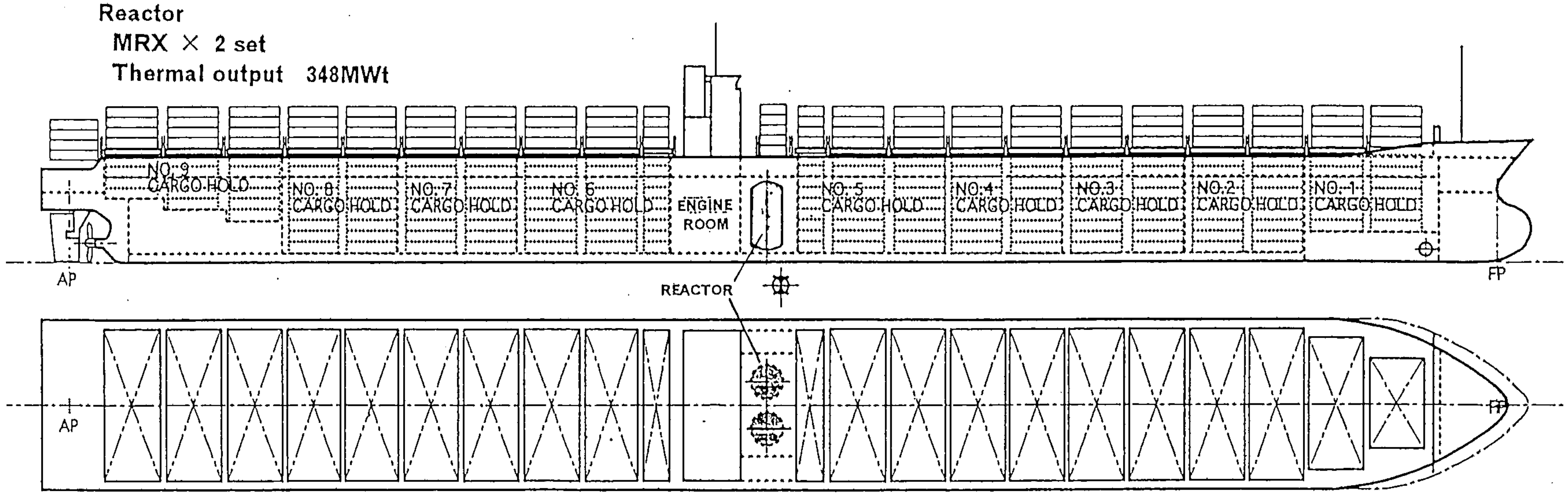


Figure 2.2 General arrangements of the high-speed nuclear container ship model

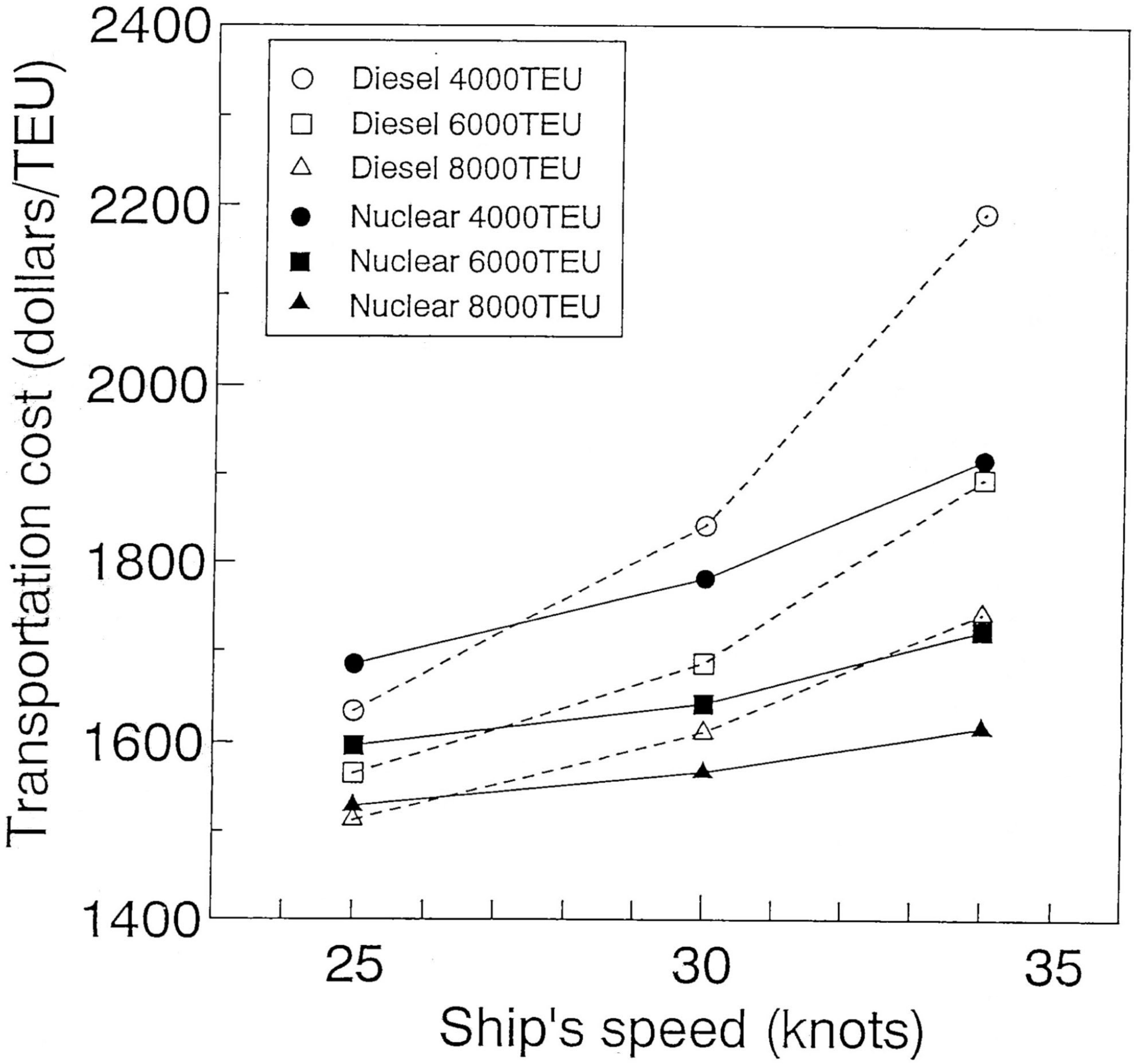


Figure 2.3 Cost evaluation of nuclear ships on the Pacific Ocean

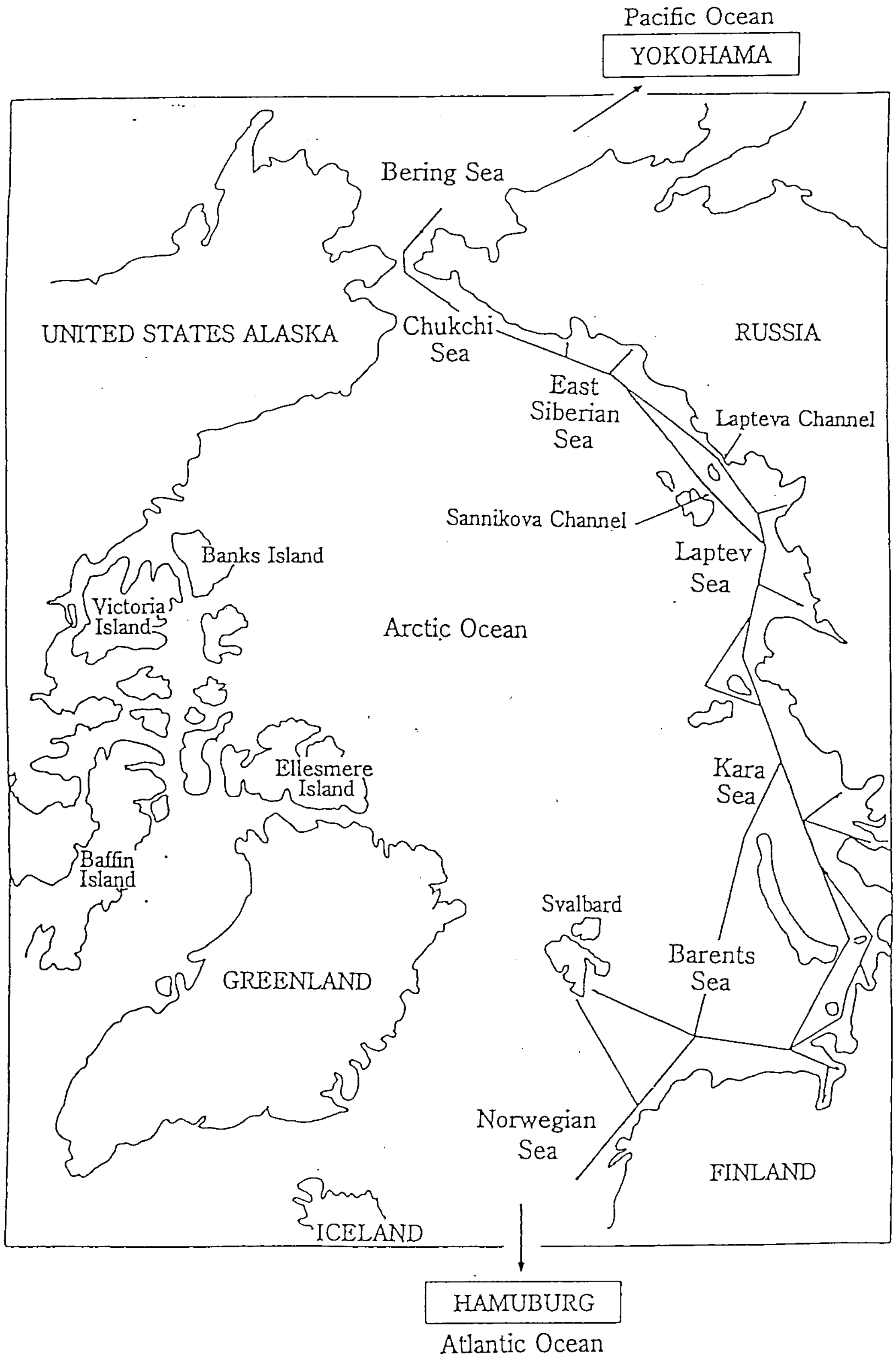


Figure 2.4 The Northern Sea Route

when sailing to Vancouver. The NSR, then, greatly shortens sailing distances compared to the conventional routes.

Table 2.4 Sailing distance from Hamburg to various destinations

	Hamburg to			
Transporting Routes	Vancouver	Yokohama	Hong-Kong	Singapore
via NSR	6,635	6,920	8,320	9,730
via Suez	15,377	11,073	9,640	8,377
via Cape of Good Hope	18,846	14,542	13,109	11,846
via Panama	8,741	12,420	13,920	15,208
via Vostochnvy sea & rail	10,240	7,015	7,820	9,180

3) Ice thickness: The ice conditions along the Arctic Ocean throughout the year vary in a three-phase cycle; freezing, thawing of ice, and water mixed with ice (ice-floes/partially frozen). Phase one is by far the longest phase; during an average year this lasts from August/September until May. In the freezing phase, the ice can reach a thickness of up to 2.5 meters (first-year ice). Phase two, thawing of the ice, is short and lasts from May until July. Phase three (ice-floes) lasts from May until August / September. Currently cargo transportation through the NSR is possible from late June or early July when the covered ice on the Arctic Seas gradually decreases, until mid-September. The thickness of first-year ice in the NSR is 2.5 meters throughout the year, and hummocked and multi-year ice may reach about 3.5 meters as the maximum. Considering the thickness of first-year ice, at least 2.5 meters of icebreaking capacity is required for the NSR sailing container ship.

4) Ship's speed: The average speed of the icebreaking general cargo ship "Norilsk" sailing through the NSR is 10.8-12.6 knots in the summer period, and 5.8-7.2 knots in the winter period, and in the case of the nuclear icebreaking lighter aboard ship "Sevmorput," the speed in summer is 12.8-15.7 knots and 7.6-10.2 knots in winter. With the speed in the summer period approximately double of that in the winter period, countermeasures for regular container shipping must be considered.

5) Navigation support system: The Arctic Ocean is supported by three networks of the radio-navigation systems (RNS) "Mars-75". Satellite navigation system (SNS), "Navigator" (U.S.) and "Glonass" (Russia) are in the development stage.

6) NSR toll: In the case of a 20,000 DWT class icebreaking cargo ship (Ice Class ULA: first

grade type) led by a powerful icebreaker, the toll is about $100,000. That is the cost of being led by a Russian icebreaker; the toll of a self-navigating icebreaker is yet unknown.

2.5 Conceptual design of a nuclear icebreaking container ship

The Shipbuilding Research Association of Japan, which has defined the technological problems and the objectives of research and development to materialize a future nuclear ship, is also conducting the project called "Study on the design aspects of nuclear ships for practical use" [7], which aims at research and development of an icebreaking observation ship, a deep-sea scientific research ship, and a high-speed container ship, that are expected to be realized soon. In this study the technological research of the NSR was carried out and the trial design of a nuclear icebreaking container ship model has been performed. The principal factors of the imaginary nuclear icebreaking container ship are as follows. **Figure 2.5** shows its general arrangements.

Type of ship	Forecastle flush decked ship	
	Engine room and reactor room: Semi-AFT	
	Steering room and accommodation space: Bow	
Principal dimensions	Loa	216.00 m
	Lpp	200.00 m
	B	32.20 m
	Bwl	31.85 m
	D	19.40 m
	d	11.00 m
	Cb	0.694
Nationality	Japan	
Adoptive rules	NK	
	SOLAS 74/78 Amend 81, 83, 88, and 89	
	MARPOL 73/74	
	IMO RES. A-491(X): Nuclear safety criteria	
	ASPPR CSC-3 equivalent	
NT	36,000 ton	
DW	21,000 ton	
Displacement	50,392 ton	
Number of containers	1,400 TEU	
Volume of ballast tank	20,000 m^3	

Volume of fuel oil tank	1,150 m^3 : heavy oil (A-oil)
Max. speed at calm sea	20 knots
Icebreaking ability	2.5 m thickness (ship's speed: 3 knots)
Propulsion	Type: Steam turbine with reduction gear: 3 sets
	Total output: 90,000 PS (30,000 PS/set)
	Steam pressure: 3.7 MPa
	Steam temperature: 285°C
Reactor	Type: Integral PWR "MRX"
	Thermal output: 300 MWt
	Steam pressure: 3.9 MPa
	Steam temperature: 289°C
Propeller	Controllable pitch propeller: 3 sets
Emergency propulsion plant	Auxiliary boiler: 1 set
Cargo handling gear	Gantry crane (30 ton): 2 sets
Bow thruster	Electric controllable pitch propeller: 1 set

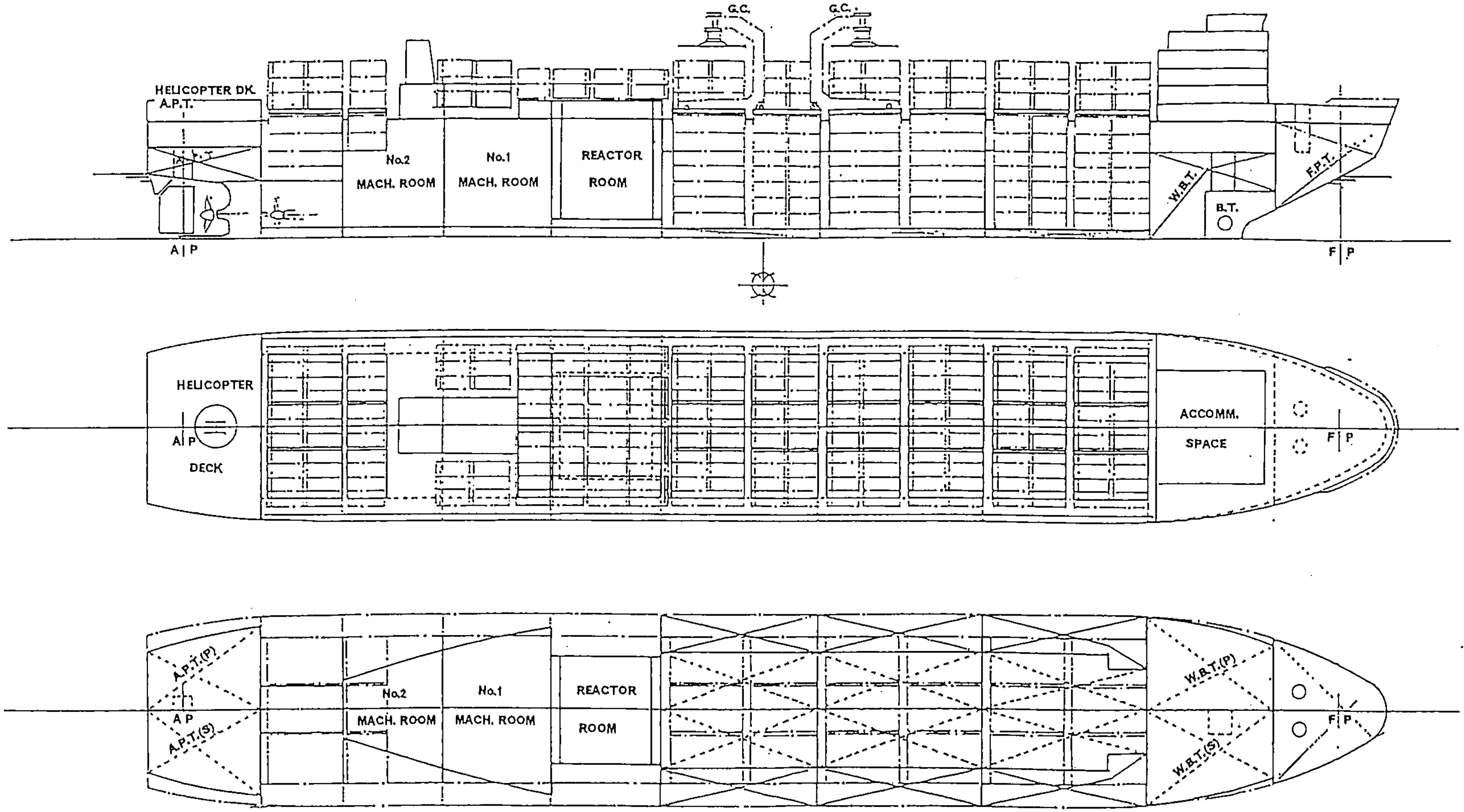


Figure 2.5 General arrangements of the nuclear icebreaking container ship model

3. The Cost Evaluation of a Nuclear Ship Sailing through the NSR and Diesel Ships Passing through the Suez Canal

In this chapter, we examine the economic potential of a nuclear icebreaking container ship sailing through the NSR as a transportation system, in comparison with diesel container ships sailing the route through the Suez Canal. The type of ships studied and their principal factors are shown in **Table 3.1**. The ships studied for the cost simulation were one nuclear ship (1,400 TEU / 20 knots) equipped with an MRX, and nine diesel ships with various numbers of containers (4,000/6,000/8,000 TEU) and varying speed (25/30/34 knots). These ships are mentioned in the second chapter, i.e., the diesel driven, high-speed, large container ships whose costs evaluation on the Pacific Ocean was prepared by the JAERI, and the nuclear icebreaking container ship designed by the Ship Building Research Association of Japan. Here, the nuclear icebreaking container ship is assumed to be able to sail throughout the year for its ability to break ice more than 2.5 meters thickness, while the cost evaluation was only made on the basis of the summer period between late July and late October. The sea route is set between Yokohama and Hamburg with a sailing distance of 22,146 miles via the Suez Canal and 13,840 miles via the NSR (Arctic sea: 6,400 miles), without any calling port on the way. Also, the toll for passing through the NSR is not taken into account because the said nuclear ship here is a self-going type icebreaker.

Provided that the ships would be put into service in 2015 and utilized for 20 years , the cost comparison using the models of one nuclear ship and nine diesel ships has been made with regard to first-year transportation cost, RFR and total cost, and the advantages and disadvantages of transportation systems, benefits and demerits for operators and shippers were studied. The definition of those cost items are as follows.

1) First-year transportation cost:

First-year transportation cost born by operators, is the cost of carrying one TEU (twenty-foot container equivalent unit) in the first year. It is the addition of various expenses for operation per year plus capital costs for the first year, divided by the number of TEU carried in a year.

$$\textit{First-year transportation cost} = \frac{\textit{Container shipping expenses (the first year)}}{\textit{Number of TEU carried in the first year}} \qquad (3.1)$$

Table 3.1 Principal factors of nuclear ship sailing through the NSR and diesel ships passing through the Suez Canal

Type	Diesel									Nuclear
Number of containers (TEU)	4,000			6,000			8,000			1,400
Ship's speed (knot)	25.0	30.0	34.0	25.0	30.0	34.2	25.0	30.0	33.5	20.0
Lpp (m)	245.0	247.0	255.0	326.0	329.0	342.0	357.0	366.0	371.0	200.0
B (m)	40.0	40.0	40.0	40.0	40.0	40.0	42.5	42.5	42.5	32.2
D (m)	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	19.4
d (m)	12.2	12.9	14.0	13.8	14.3	14.9	15.2	15.5	16.1	11.0
Cb	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.694
Displacement (ton)	70,400	75,400	84,200	105,800	111,000	120,300	135,700	142,700	149,500	50,392
GT (ton)	59,600	59,100	59,400	76,300	76,000	77,900	85,700	87,200	87,000	36,000
DW (ton)	48,400	49,500	52,400	70,400	71,800	74,400	92,600	94,400	96,500	21,000
LW (ton)	22,000	25,900	31,800	35,400	39,200	45,900	43,100	48,300	53,000	7,000
SHP (PS)	60,300	140,000	280,000	75,800	151,800	280,000	88,100	171,000	280,000	90,000
Thermal output (MWt)	—	—	—	—	—	—	—	—	—	300
Number of shafts	1	2	4	2	3	4	2	3	4	3

2) RFR (required freight rate):

Similarly, RFR is the cost born by operators in order to carry one TEU during the ship's life. It is calculated by dividing all the container shipping expenses by the number of total TEU carried during ship's life.

$$RFR = \frac{\textit{Container shipping expenses (ship's life)}}{\textit{Number of TEU carried during ship's life}} \qquad (3.2)$$

3) Total costs:

Total costs are the expenses to be paid by shippers, that are described in the following. They are often used for comparing the expenses of different traffic routes and consist of ;

$$\textit{Total cost} = \textit{freight} + \textit{premium} + \textit{interests} + \textit{storage expenses} + \textit{sales opportunity costs} \qquad (3.3)$$

The assumptions for the calculation of each cost item are derived from the report entitled "Report of analysis and evaluation on the economy of nuclear merchant ships" (1992) [8], presented by Ishikawajima-Harima Heavy Industries Co. Ltd.,. In this report, a cost evaluation of the nuclear ships and diesel ships, considering the experiences obtained from the diesel ships actually built and operated, has been studied. The results of the cost evaluation were converted into the numerical formulas by the JAERI, in the form of the report entitled "Study on a total system concerning operation of nuclear ships" (1994) [5]. The assumptions and calculations of our study are based on the numerical formulas of the said JAERI report.

3.1 Calculation formulas for first-year transportation cost

As before, the first-year transportation costs borne by operators are the costs of carrying one TEU in the first year. It is the sum of operating expenses (such as crew expenses, repair charges, insurance, office expenses, ship stores expenses, etc.), voyage expenses (such as fuel costs, port charges, container-related expenses, etc.), and construction plus capital costs for the first year, divided by the number of TEU carried in a year, provided that a ship would be put into service in 2015. By around the year, some nuclear container ships will be in practical use after the developing period. Considering the emission reduction target for SO_x and NO_x to be enforced in 2000 by the International Maritime Organization (IMO), and the concepts of the

European Community (EC) for "taxes on CO_2 emissions," the clean air costs are included in the container shipping expenses [5]. The clean air costs for the nuclear ship are not taken into account in normal voyages, while nuclear energy insurance will be taken out in case the ship has any trouble. The principal items for the calculation of the first-year transportation cost are specified as follows.

(1) Operating expenses

1) Construction costs (in millions of dollars):

Considering that the building period is longer for a nuclear ship than a diesel ship, the construction costs were introduced by the following formulas using the light weight (*LW*), shaft horsepower (*SHP*) and reactor thermal output (W_t) as parameters.

$$Construction\ costs\ (diesel) = (0.0032 \times LW + 2.85 \times (SHP \times 1000)^{0.6}) \times 1.08$$
$$Construction\ costs\ (nuclear) = (0.0035 \times LW + 3.55 \times (SHP \times 1000)^{0.6} + 93 \times (W_t / 200)^{0.4}) \times 1.12 \quad (3.4)$$

2) Capital costs for the first year (in millions of dollars):

It is assumed that the initial costs are fully financed by a loan, and the principal and interest will be repaid equally in balance for a 12-year period.

$$Capital\ costs = \frac{P \times R}{1 - \frac{1}{(1+R)^N}} \quad (3.5)$$

P: construction costs (millions of dollars)
R: interest (7.0%),
N: repayment period (12 years)

3) Crew expenses:

Crew expenses (diesel): 1.7 million dollars (14 crew)
Crew expenses (nuclear): 2.1 million dollars (17 crew) (3.6)

4) Repair charges (in millions of dollars):

These include the charges for hull and engine repairs, which will increase year by year. Additional charges will be incurred in the event of drydocking. Therefore, the average value for a 20-year period is regarded as the annual repair charges and is multiplied by 1.03 [5] which is the average secular index. (B: breadth, D: depth, n: ship's age)

Repair charges (diesel)

$$= (Lpp^{0.75} \times (B + D)^{0.75} \times 2.3 \times 10^{-4} + SHP^{0.5} \times 1.7 \times 10^{-3}) \times 1.03^{n}$$

Repair charges (nuclear)

$$= (Lpp^{0.75} \times (B + D)^{0.75} \times 2.3 \times 10^{-4} + SHP^{0.5} \times 2.5 \times 10^{-3}) \times 1.03^{n} \quad (3.7)$$

5) Hull insurance:

The insurance is estimated by multiplying the construction costs by the insurance premium rate.

Hull insurance (diesel): 0.28% of the construction costs
Hull insurance (nuclear): 0.56% of the construction costs (3.8)

6) P&I insurance:

P&I insurance: 4.3 dollars per gross tonnage per year (3.9)

7) Nuclear energy insurance (nuclear ship only):

Liability insurance for damage: 0.9 million dollars per year
Contract indemnity for damage: 0.036 million dollars per year (3.10)

8) Office expenses:

A nuclear ship needs additional fees for the nuclear fuel management and land support operators.

Office expenses (diesel): 4.0 million dollars per year
Office expenses (nuclear): 4.3 million dollars per year (3.11)

9) Lubricant costs (in dollars):

The lubricant costs are estimated by multiplying the amount of cylinder oil and system oil used per year by the average value of the lubricating oil fees (cylinder oil: 1.36 dollars/liter; system oil: 1.28 dollars/liter). As the main engine of the nuclear ship is assumed to be a steam turbine that consumes very little turbine oil, the lubricant costs are not included.

$$\text{Lubricant costs (cylinder oil)} = 8.1 \times SHP \times 1.36$$
$$\text{Lubricant costs (system oil)} = 1.5 \times SHP \times 1.28 \quad (3.12)$$

10) Ship store expenses:

Ship store expenses (diesel): 0.09 million dollars per year

Ship store expenses (nuclear): 0.12 million dollars per year (3.13)

11) Sundry expenses for ships:

Sundry expenses for ships: 0.076 million dollars per year (3.14)

(2) Voyage expenses

1) Fuel costs for a diesel ship (in dollars):

Using an average fuel oil fee of 156 dollars per ton and shaft horsepower of the main engine (*SHP*), the calculation was done as follows;

$$Fuel\ costs = (0.73 \times SHP \times 156) / 1000 \quad (3.15)$$

2) Fuel cycle costs per year for a nuclear ship (in millions of dollars):

Using an average nuclear fuel fee of 3.0 million dollars per ton and 0.727 tons of fuel consumed per year, the calculation is made from the thermal output of the reactor (W_t).

$$Fuel\ cycle\ costs = 0.727 \times W_t / 100 \times 3.0 \quad (3.16)$$

3) Fuel exchange costs per year for a nuclear ship (in millions of dollars):

Assuming nuclear fuel is exchanged once every four years, the fuel exchange costs come from the following formula.

$$Fuel\ exchange\ costs = (0.043 \times (15 + SHP / 10{,}000)) / 4 \quad (3.17)$$

4) Waste disposal costs per year for a nuclear ship (in millions of dollars):

$$Waste\ disposal\ costs = 0.057 \times (SHP / 1{,}000)^{0.6} \quad (3.18)$$

5) Port charges:

Port charges: 3.8 dollars per gross tonnage for one roundtrip (3.19)

6) Container-related expenses:

Cargo handling fees, container lease fees, agency fees, etc., are included in this calculation.

Container-related expenses: 1,200 dollars per TEU for one way voyage (3.20)

7) Miscellaneous voyage expenses:

Miscellaneous operating expenses: 0.02 million dollars for one roundtrip (3.21)

8) Clean air costs for a diesel ship:

Considering the emission reduction targets for SO_x and NO_x to be enforced in 2000 by the International Maritime Organization (IMO), and the concepts of the European Community (EC) for "taxes on CO_2 emissions," the clean air costs are estimated as follows.

· NO_x countermeasure costs (in dollars):

There will be a 5 percent increase in the amount of fuel due to the rising combustion temperature in the cylinders of the main engine.

$$NO_x \text{ countermeasure costs} = \text{amount of fuel} \times 0.05 \times \text{fuel fee} \qquad (3.22)$$

· SO_x countermeasure costs (in dollars):

There will be a 50 percent increase in the fuel fee by using low-sulfur fuel oil due to the introduction of the greenhouse effect related regulations.

$$SO_x \text{ countermeasure costs} = \text{fuel fee} \times 0.5 \qquad (3.23)$$

· Taxes on CO_2 emissions (in millions of dollars):

Assuming that the annual tax will be ten dollars per one ton of CO_2 emission, and it increases in proportion to the shaft horsepower of the main engine.

$$\text{Taxes on } CO_2 \text{ emissions} = 2.3 \times SHP \times 10^{-5} \qquad (3.24)$$

9) Suez Canal toll for a diesel ship (one way):

Converting the gross tonnage into Suez tonnage and finding the Suez Canal toll from the toll table. Mooring and unmooring fees and launch hires are added to the toll.

Toll	*specified on the table*	
Mooring & unmooring fees	*1,500 dollars*	
Launch hires	*150 dollars*	(3.25)

(3) Operating time

1) Working days per year:

Assuming a ship docks every two years and the exchange of nuclear fuel is made once every four years, the working days per year are shown in **Table 3.2**.

Table 3.2 Working days per year

	Undocking	Docking	Fuel exchange
Diesel	360	345	---
Nuclear	360	345	320

Then, the average working days per year during 20 years of the ship's life are ;

Average working days (diesel) : 352 days

Average working days (nuclear): 346 days (3.26)

2) Days required for a roundtrip voyage:

Assuming that the ship will be in harbor for three days, two days for disposal goods and customs formalities, and four days for delays (including spare for passing through the Suez Canal or the NSR), the term for a roundtrip voyage can be calculated as follows:

Days required for a round voyage = (Sailing distance / Ship's speed / 24) + 9 (3.27)

3) Container loading rate:

Container loading rate: 85 % (3.28)

3.2 Calculation formulas for the Required Freight Rate

The RFR is the transportation cost of carrying one TEU during a ship's life. It is the sum of all the container shipping expenses such as capital costs, operating expenses, voyage expenses and decommissioning fee for a nuclear ship, divided by the number of TEU carried during the ship's life, assuming that the ship would be put into service in 2015 and that the life would be 20 years. The principal items for the calculation formulas of the RFR are as follows.

· **Capital costs**

· **Operating expenses**

Crew expenses, Repair charges, Hull insurance, P&I insurance, Nuclear energy insurance, Office expenses, Lubricant costs, Ship store expenses, Sundry expenses for ships

· **Voyage expenses**

Fuel costs, Nuclear fuel cycle costs, Nuclear fuel exchange costs, Waste disposal costs, Port charges, Container-related expenses, Miscellaneous voyage expenses, Clean air costs, Suez Canal toll

· **Final-year special costs**

Scrap receipt, Decommissioning expenses

The value in the first year must be reduced in the calculations of various overall shipping costs during a ship's life. As the value of many cost items will change due to inflation, they can be calculated based on actual expenses. The capital costs and insurance, however, must be calculated based on current prices although the actual expenses incurred are constants during a ship's life. Therefore, the cost items other than capital costs and insurance are integrated for 20 years on the basis of the container shipping costs calculated for the first year. On the other hand, capital costs, insurance and final-year special costs are calculated as follows.

1) Capital costs:

In 12 years principal and interest equal repayment system, the capital costs, namely the sum of principal repayment and the interest on the balance can be calculated as follows.

$$Capital\ costs = \sum_{n=1}^{N} \left[\frac{P_O}{N} / (1+r)^n + \left\{ P_O - \frac{P_O}{N}(n-1) \right\} \times \frac{R}{(1+r)^n} \right]$$

N : repayment period (12 years) (3.29)

r : inflation rate (6.1%)

P_O : actual construction costs (millions of dollars)

R : interest (7.0%)

Where the actual construction costs can be calculated as follows.

$$P_O = \frac{P}{4} \left\{ (1+R)^{M/12} + (1+R)^{M/18} + (1+R)^{M+36} + 1 \right\} + P \times 0.01$$

P : construction costs (millions of dollars) (3.30)

M : building period diesel: 24 months

nuclear: 36 months

2) Insurance:

$$Insurance = \frac{(1+r)^Y - 1}{r \times (1+r)^Y} \times I_P$$

r : inflation rate (6.1%) (3.31)

Y : ship's life (20 years)

I_P : insurance (in the first year)

3) Final-year special costs;

The final-year special costs are estimated as follows assuming that the ship is dismantled.

・ Scrap receipt (income):

Scrap receipt: 230 dollars per light weight (LW) (3.32)

・ Decommissioning expenses for a nuclear ship (in millions of dollars):

The calculation of the decommissioning expenses is based on a cost simulation of the Nuclear Regulatory Commission (NRC) and Battel Pacific North West Lab. (BPNL). The decommissioning expenses are 30 percent higher than the said cost simulation results.

$$Decommissioning\ expenses = 13 + (0.03 \times SHP / 1{,}000) \quad (3.33)$$

3.3 Calculation formulas for total costs

The total costs consist of freight, premium, interest or cost of capital for the transportation period, interest or cost of capital for the storage period, storage expenses, and sales opportunity costs to be paid by shippers, are useful to compare the costs of using different traffic media. These expenses will fluctuate depending on the means of transportation and the number of days used for transportation. The calculation formulas are as follows.

(1) Distribution expenses

1) Freight (F):

Assuming freight is in proportion to the unit weight (freight ton) of commodities, the freight is calculated as follows.

$$F = q \times f \quad \text{(dollars)} \quad (3.34)$$

q : annual volume of commodity carried (TEU

f : freight of the commodity; freight costs (dollars/freight ton)

2) Premium (I):

Premium is determined by multiplying premium rate [5] and the freight.

$$I = i \times q \times p \quad \text{(dollars)} \qquad (3.35)$$

i : premium rate (0.27%)

q : annual volume of carried commodity (TEU)

p : value of the commodity (dollars/freight ton)

3) Interest or cost of capital for the transportation period (R_t):

Assuming that the time lag between buying and selling is in proportion to the transportation period, the interest will be;

$$R_t = r_t \times T/365 \times q \times p \quad \text{(dollars)} \qquad (3.36)$$

r_t: interest (10%)

T : transportation period (days)

q : annual volume of carried commodity (TEU)

p : value of the commodity (dollars/freight ton)

(2) Stock costs

Supposing that the stock of commodities decreases at a certain rate, and new commodities will be stocked with the same cycle as the cargo transportation period, and the stock of commodities will be decreased to 20 percent until the next charge is made.

1) Interest or cost of capital for the storage period (R_s):

Assuming the interest for the storage period is a yield to the whole commodity value at a certain rate during the storage period, the interest can be shown as follows. While 20 percent of the storage is assumed not to be transported and is constant through a year, so the interest for this portion of stock is not included.

$$R_s = r_s \times T/365 \times q \times p \quad \text{(dollars)} \qquad (3.37)$$

r_s: interest (10%)

T : transportation period (days)

q : annual volume of carried commodity (TEU)

p : value of the commodity (dollars/freight ton)

2) Storage expenses (S):

Storage expenses are the product of the annual value of commodities by the stock-shipment ratio [5], when the stock is full.

$$S = 1.25 \times \alpha \times T / 365 \times q \times p \qquad \text{(dollars)} \qquad (3.38)$$

α: stock-shipment ratio (20%)
T : transportation period (days)
q : annual volume of carried commodity (TEU)
p : value of the commodity (dollars/freight ton)

(3) Sales opportunity costs

The sales opportunity costs (O) are the devaluation of the sales value caused by losing sales opportunities during transportation and storage period. In this study, we assume that the cargo will completely lose its value in two years and that sales opportunity costs will be equal to the sales value after the certain period of transportation. We have assumed that the sales opportunity costs are zero when the goods are carried by air spending four days, and the period to fully lose the value of cargo (T_O) is two years. The cost is calculated with the simplified formula as follows.

$$O = (T - 4) / T_O \times q \times p \qquad \text{(dollars)} \qquad (3.39)$$

T : transportation period (days)
T_O : period to lose the value of commodity (days)
q : annual volume of carried commodity (TEU)
p : value of the commodity (dollars/freight ton)

In this study electrical appliances A and B referred as the commodities shown as **Table 3.3**. **Table 3.4** shows the terms to calculate the total costs. The freight cost is the cost per unit weight, which are calculated from the cost per TEU. **Table 3.4** also includes the transportation period for each shipping. Nine days are included, for in harbor, the disposal goods and customs formalities etc., in the transportation period too.

Table 3.4 Terms to calculate the total costs <diesel ships / a nuclear ship>

Type	Diesel									Nuclear
TEU	4,000			6,000			8,000			1,400
Knots	25	30	34	25	30	34.2	25	30	33.5	20
Freight cost (f) <dollars>	69	77	89	65	70	78	62	66	71	108
Transportation period (T) <days>	23	20	18	23	20	18	23	20	18	19
Premium rate (i)	0.27%									
Interest (r_l, r_S)	10%									
Stock-shipment ratio (α)	20%									

Table 3.3 Type of goods to be carried

	Electrical appliance	
	A	B
Weight	3.0 kg	1.0 kg
Volume	8 m^3 / ton	6 m^3 / ton
Value per unit weight (kg)	1,250 dollars	125 dollars
Number of carried commodities	200,000	200,000
Annual volume of carried commodities	600 ton 4,200 freight ton	200 ton 1,100 freight ton
Annual amount of carried commodities	250 million dollars	25 million dollars
Value per freight ton	60 thousand dollars	23 thousand dollars

3.4 Calculation results and their review

1) First-year transportation costs and RFR

Figure 3.1 shows the first-year transportation costs of carrying one TEU (20-foot container equivalent unit) in the first year. The first-year transportation costs for a transportation period of 19 days refer to the nuclear icebreaking container ship sailing through the NSR, and the transportation costs for transportation periods of 18, 18.5, 20, and 23 days refer to the diesel container ships passing through the Suez Canal at speeds of 34 knots, 33.5 knots, 30 knots and 25 knots, respectively. As the nuclear ship will have an ability to break ice of more than 2.5 meters thickness with 90,000 PS of output, and due to the installation of the reactor, the construction costs of a nuclear ship will be substantially high. Therefore, the first-year transportation costs of a nuclear ship are much higher than those of diesel ships. **Figure 3.2** shows the RFR results, which are the transportation costs of carrying one TEU during ship's life. Although the RFRs of all ships are lower compared to first-year transportation costs, the RFRs are higher for the nuclear ship than for the diesel ships. **Figure 3.3** compares the transportation costs of the nuclear ship and the 4,000 TEU carried diesel ships. The declining rate from the first-year transportation costs to the RFRs is bigger for the nuclear ship compared to those of the diesel ship. Therefore, if a ship is utilized for more than 20 years, as referred in this study, the nuclear icebreaking container ship will be more economical.

2) Total cost

Figure 3.4 shows the total costs per unit weight (freight ton) in relation to the transportation period. The total costs for a transportation period of 19 days are calculated from the freight cost for the nuclear ship sailing through the NSR. Similarly, the total costs for transportation periods of 18, 20, and 23 days are calculated from the freight costs unit weight for the 6,000 TEU carried diesel ships passing through the Suez Canal. **Figure 3.4** shows that the total costs will increase for both electrical appliances A and B in the case where the transportation period is long.

Figure 3.5 compares the total costs of the nuclear ship and the 6,000 TEU carried diesel ships carrying electrical appliance A, and **Fig. 3.6** compares the total costs for carrying electrical appliance B. The freight shares two to eight percent of the total costs in the case of electrical appliances A and B. If the transportation period is extended, the total costs will be higher due to the increase of storage expenses and sales opportunity costs. Comparing the total costs of the nuclear ship (20 knots) and the diesel ship (25 knots), the diesel ship is at a disadvantage in this case. Consequently, the total costs tend to be lower when the transportation period is shorter. The NSR will have an advantage over the conventional routes if the good to be carried are well considered, such as high value commodities or commodities need to shorten the period between the production and the disposal by sale.

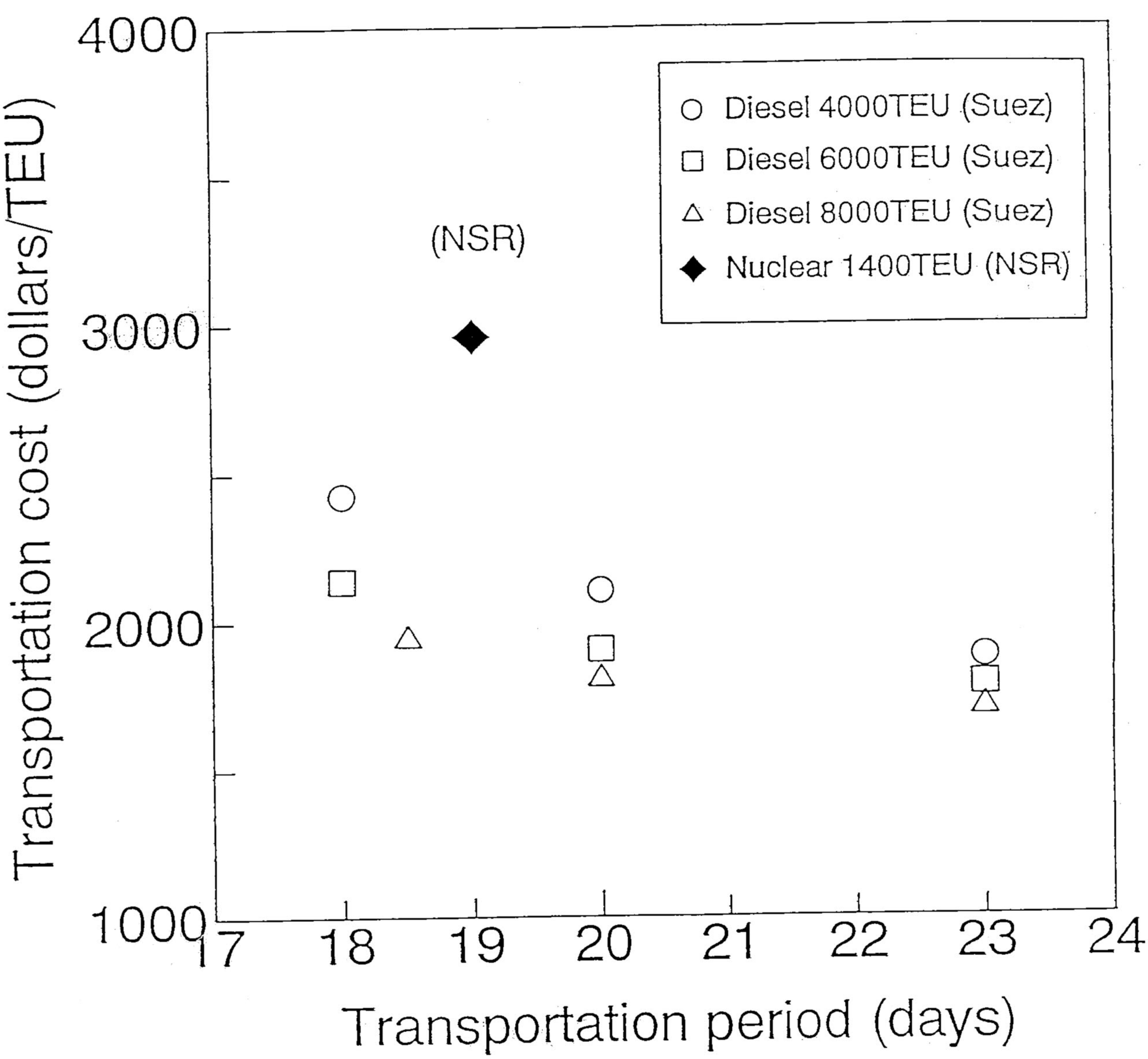


Figure 3.1 Comparison of first-year transportation costs between the NSR and the route through the Suez Canal

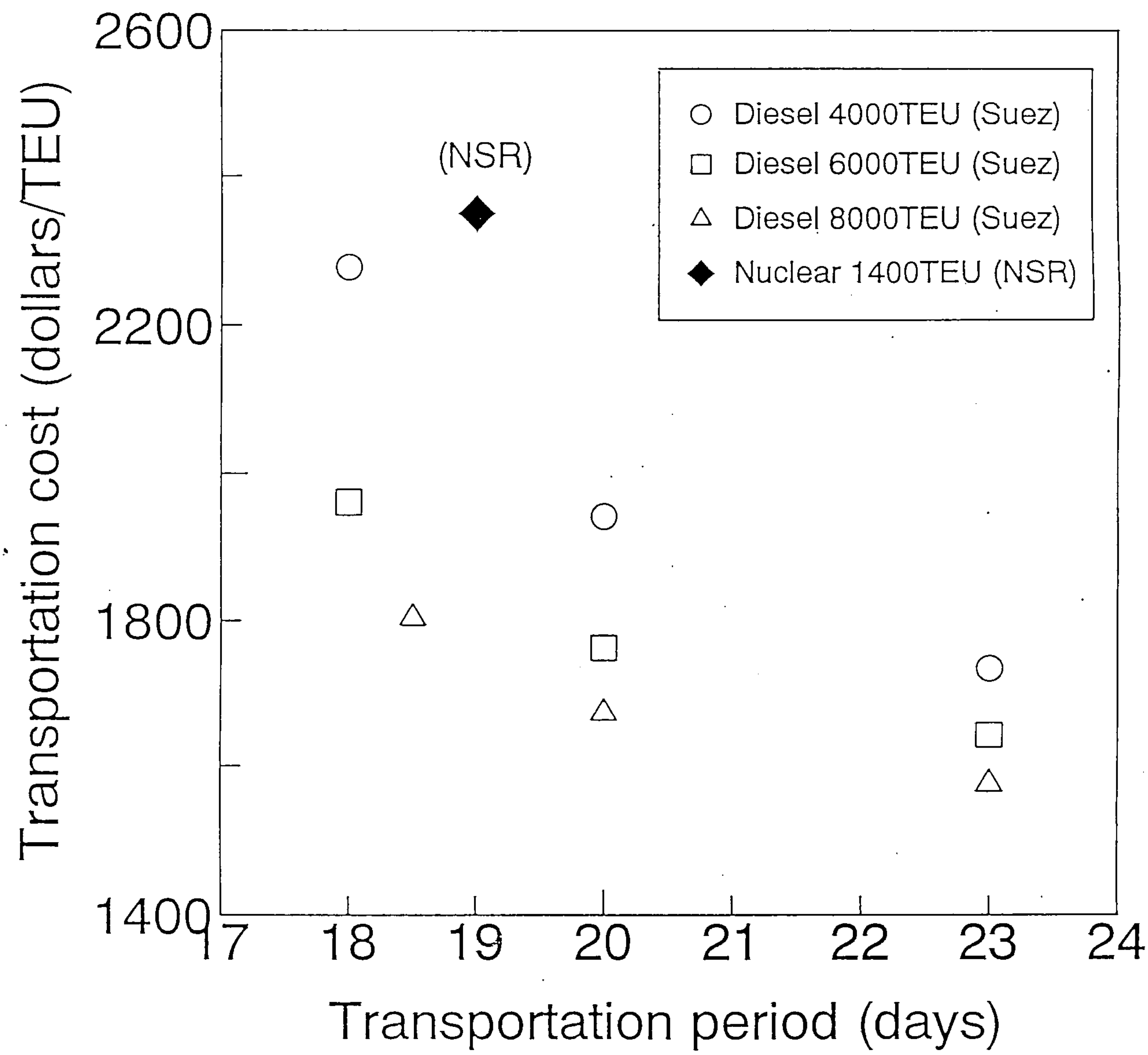


Figure 3.2 Comparison of RFRs between the NSR and the route through the Suez Canal

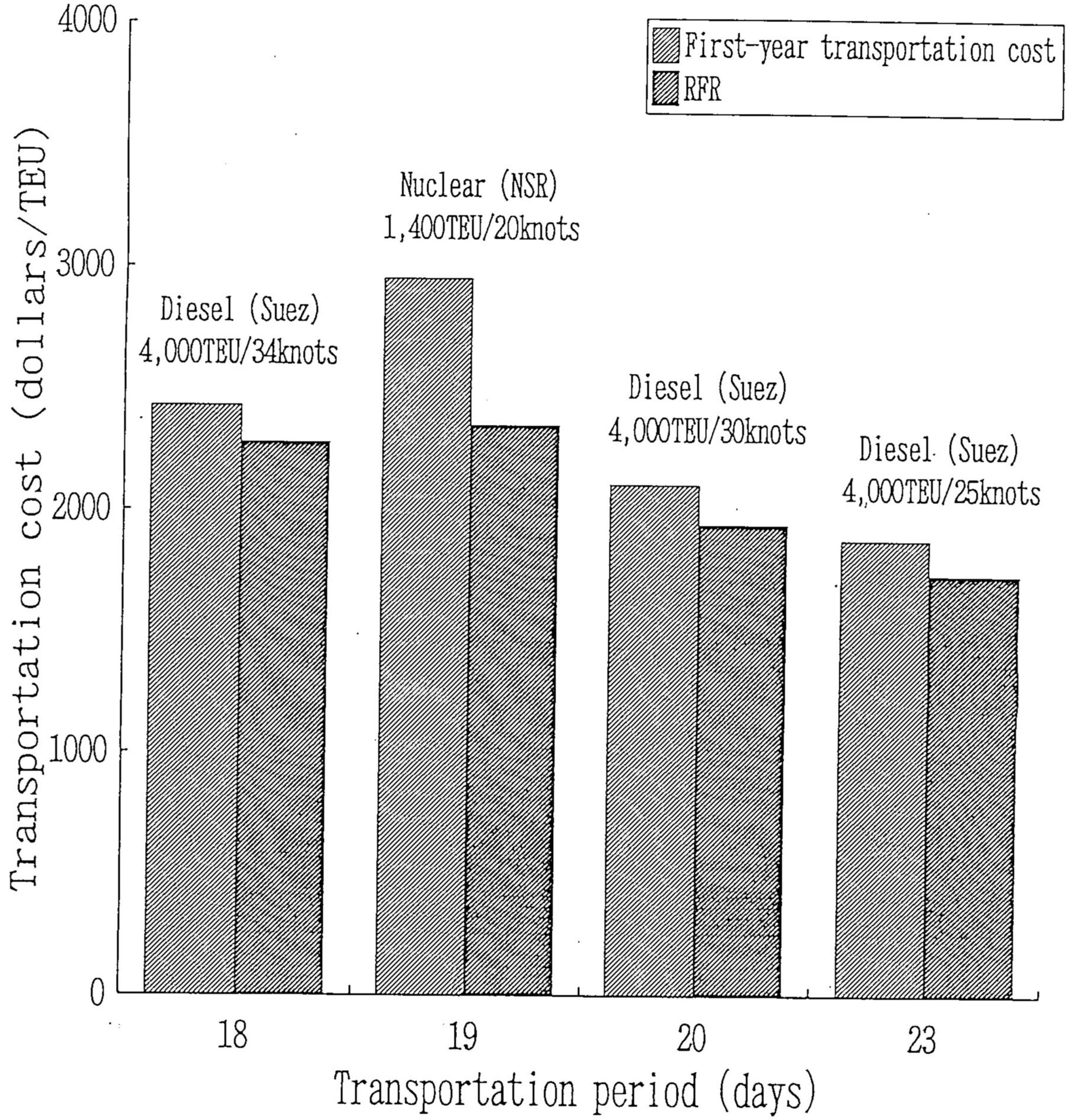


Figure 3.3 Comparison of first-year transportation costs and RFRs between the NSR and the route through the Suez Canal

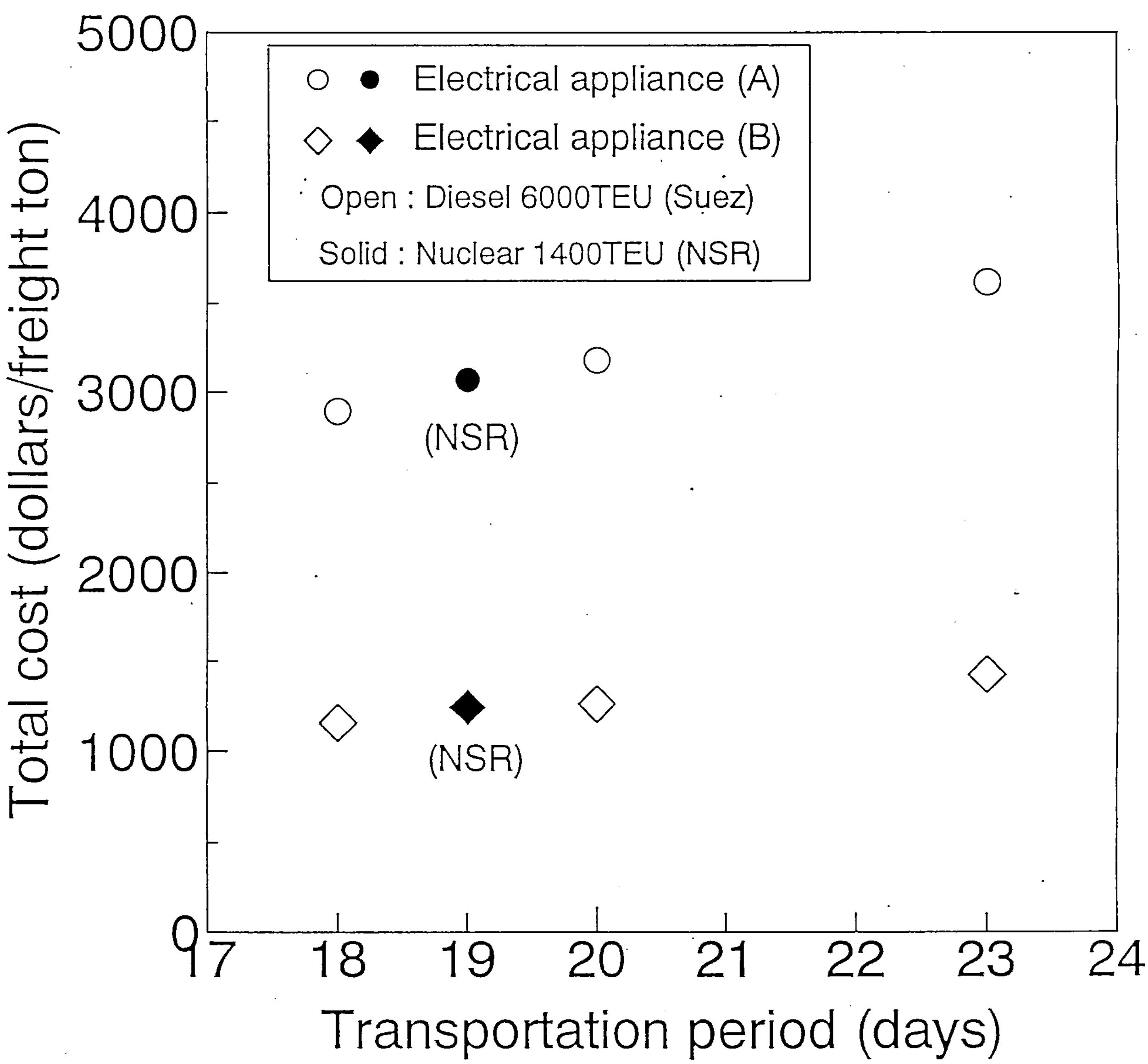


Figure 3.4 Comparison of total costs between the NSR and the route through the Suez Canal

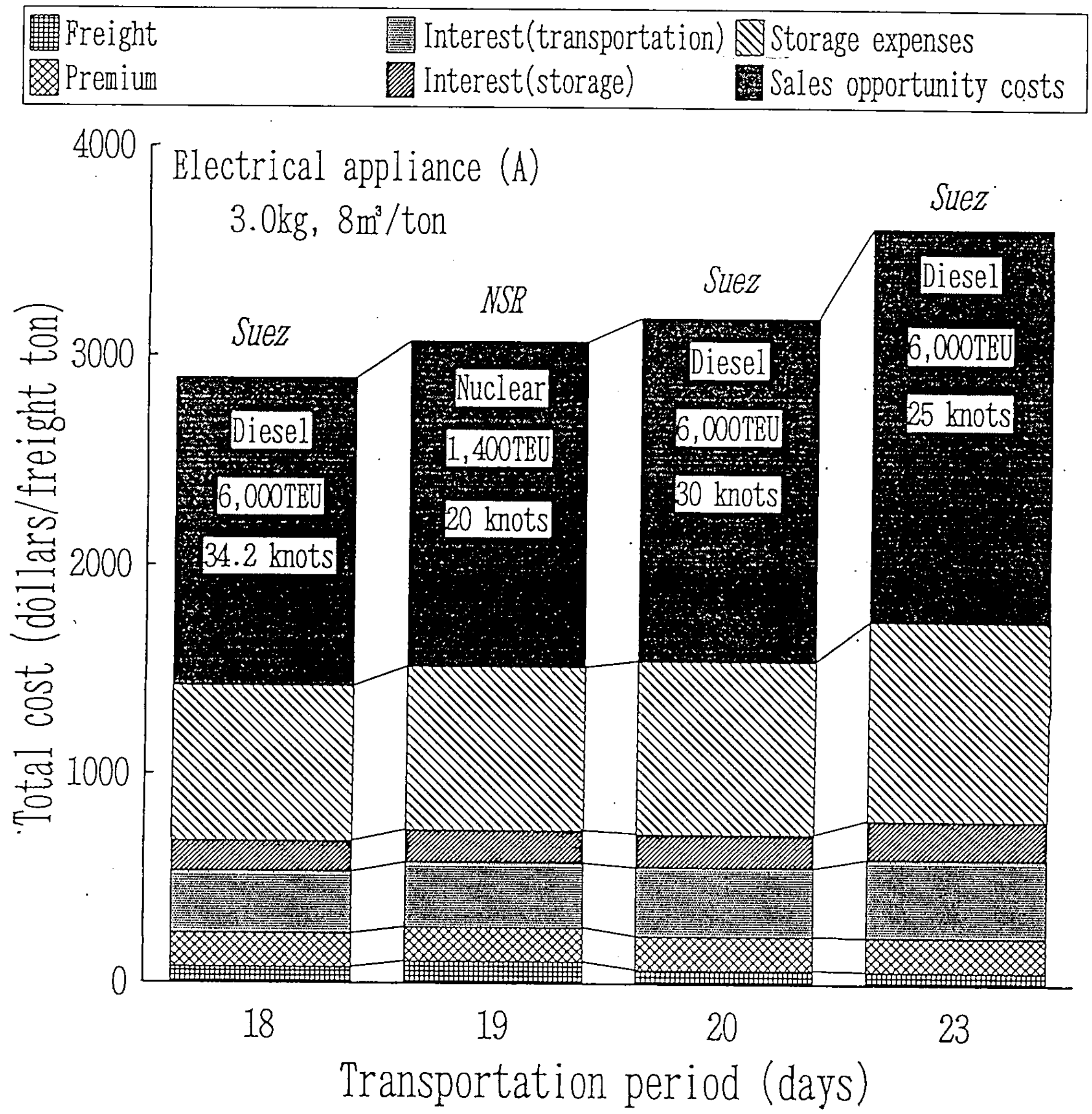


Figure 3.5 Itemization of total costs for carrying electrical appliance A using the NSR and the route through the Suez Canal

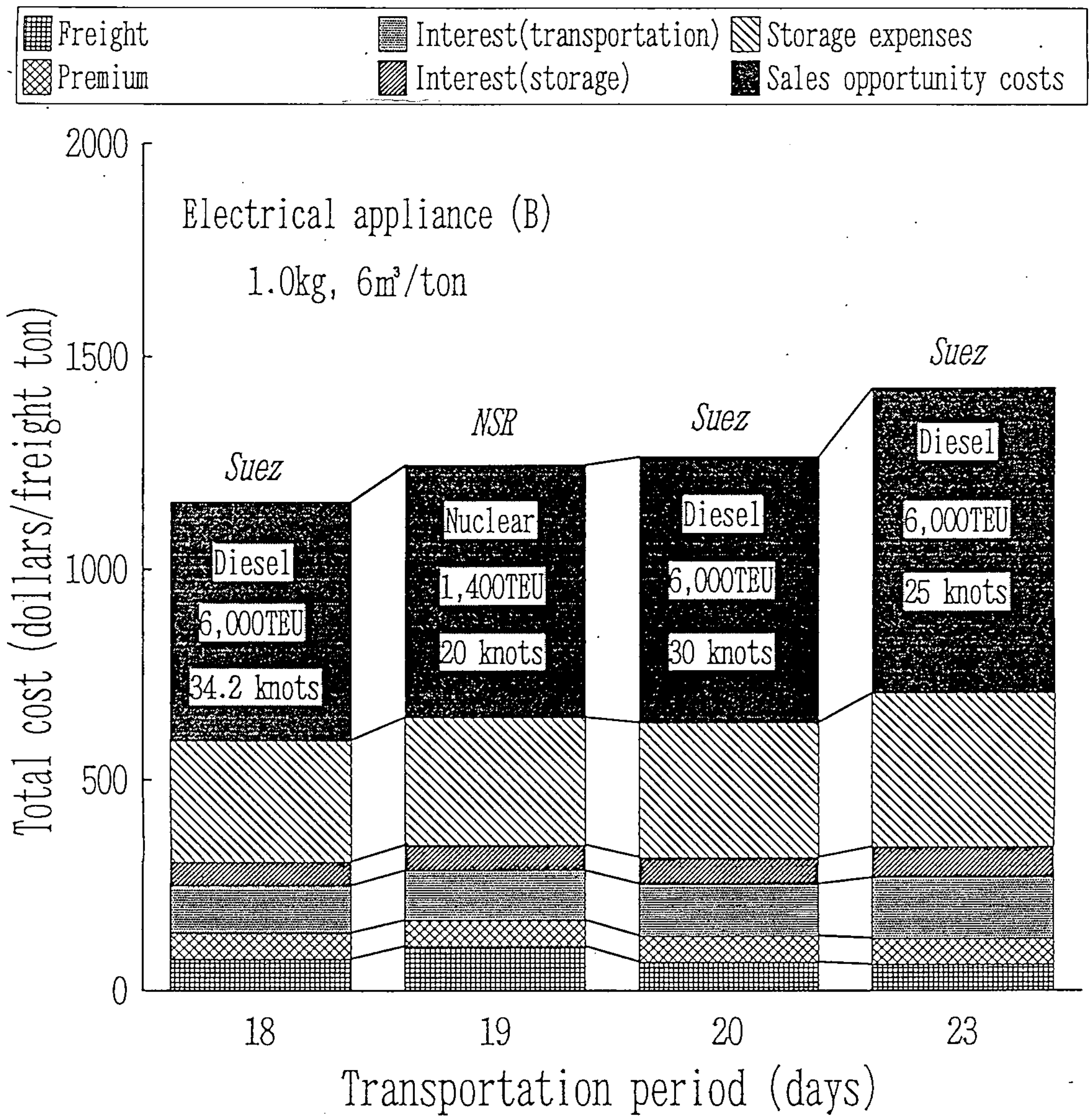


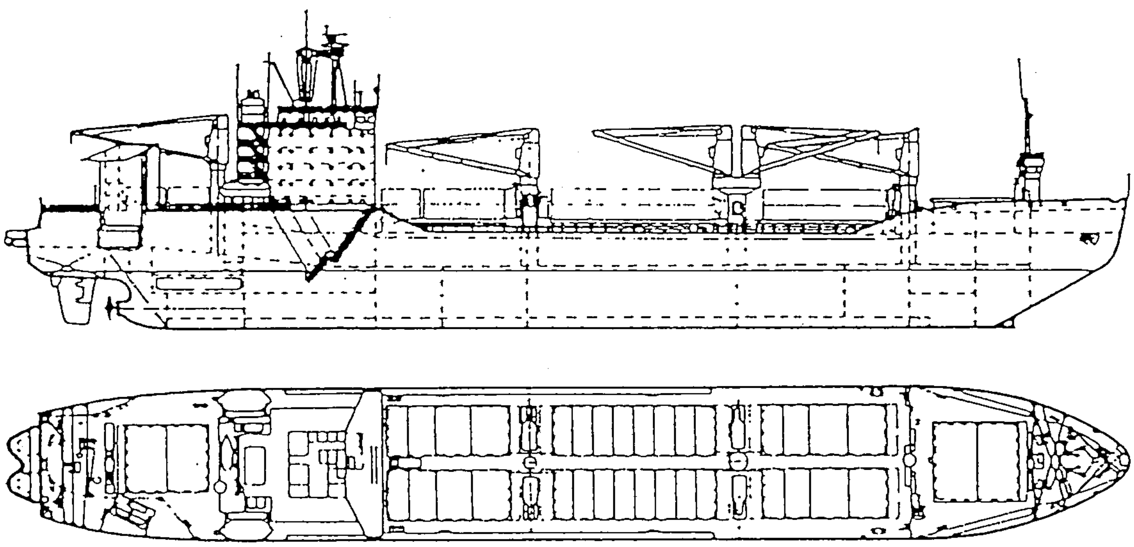
Figure 3.6 Itemization of total costs for carrying electrical appliance B using the NSR and the route through the Suez Canal

4. The Cost Evaluation of a Nuclear Ship and a Diesel Ship Sailing through the NSR

Several cargo ships now sail along the Arctic coast. Most of them sail through the NSR led by a powerful icebreaker to which icebreaker fees, pilotage fees, etc. are due. For examination of the economic potential of a self-going type icebreaking container ship sailing through the NSR as a transportation system, we have compared the ship-operating and container shipping expenses of a nuclear icebreaking container ship and an existing diesel container ship, both sailing through the NSR. We have also conducted research to determine the characteristics of cargo that could be carried economically by using a nuclear icebreaking container ship sailing through the NSR.

The ships studied for the cost simulation were the icebreaking general cargo diesel ship "Norilsk" and the nuclear icebreaking container ship mentioned in the second chapter. The "Norilsk," which can carry bales and grains in addition to containers, is a so-called cargo ship for many applications. The type of ships studied and its principal particulars are shown in **Fig. 4.1**. The payload capacity of the "Norilsk" is 576 TEU plus the space of 37,000 for bales and grains. Apparently she can carry about 2,000 TEU by turning this volume into TEU. However, even in the case of a conventional container ship sailing on the Pacific Ocean, it is impossible for a 18,000 Gross tonnage class container ship to carry 2,000 TEU. Therefore, considering the capacity of payload containers of the conventional container ships, we assumed that the "Norilsk" can carry 1,200 TEU.

Provided that the ships will be put into service in 2015 when the nuclear container ships are feasible in the operation after the developing period and utilized for 20 years, the cost comparison using the models of a nuclear ship and the diesel ship has been made regarding first-year transportation cost, RFR and total cost. The cost evaluation this time was only made on the basis of the summer period, i.e., the speeds of the diesel ships are 10, 13.5, and 17 knots, while that of the nuclear ship is 20 knots. The route is set between Yokohama and Hamburg with a sailing distance of 13,840 miles, and the ships call at no port on the way. Here, the diesel ship must pay an NSR toll, but the nuclear ship does not for its own sailing. The types of ship studied and their principal factors are shown in **Table 4.1**.



Built at the Shipbuilding Yard Wörtsilö, Turku, Finland, 1982				Ship's type The single-screw, double-deck motor ship with long forecastle, long poop, intermediate engine room and house, corner ramp, ice-breaker bow and transom stern			
General				Main particulars			
Classification KM ⊕Y ∧ A [2] A2				Length o.a.		m	173.5
Register tonnage	gross	g.r.t.	17.910	Length b.p.		m	159.6
	net	n.r.t.	9.484	Breadth moulded		m	24.0
Service speed	full-loaded	knots	17.0	Depth moulded		m	15.2
	in ballast	knots	17.6	Summer load-line draft		m	10.5
Navigating range		miles	16.000	Loaded displacement		t	30,758
Crew		pers.	39	Deadweight		t	19,942
Height of mast above the base-line		m	51.0	Loading capacity		t	15,648
Capacity	bale	m^3	25.300	Light draft	forward	m	1.10
	grain	m^3	31.185		aft	m	7.45
	containers	TEU	576	Loading capacity per 1 cm draft		tpcm	
				Type of hatch-covers	Upper deck	Tweendecks	
					end-rolling	hinged to ends	

Figure 4.1 General cargo ship "Norilsk"

Table 4.1 Principal factors of the nuclear ship and diesel ship sailing through the NSR

Type	Diesel			Nuclear
Number of containers (TEU)	1,200			1,400
Ship's speed (knot)	10.0	13.5	17.0	20.0
Lpp (m)	159.6	159.6	159.6	200. 0
B (m)	24.0	24.0	24.0	32.2
D (m)	15.2	15.2	15.2	19.4
d (m)	10.5	10.5	10.5	11.0
Displacement (ton)	30,758	30,758	30,758	50,392
GT (ton)	17,910	17,910	17,910	36,000
DW (ton)	19,942	19,942	19,942	21,000
LW (ton)	10,816	10,816	10,816	7,000
SHP (PS)	4,300	14,400	21,000	90,000
Thermal output (MWt)	—	—	—	300
Number of shafts	1	1	1	3

4.1 Calculation formulas for first-year transportation cost

The first-year transportation cost is calculated in the same way as in the third chapter. The items for the calculation formulas of the first-year transportation cost are as follows.

- **Operating expenses**

Crew expenses, Repair charges, Hull insurance, P&I insurance, Nuclear energy insurance, Office expenses, Lubricant costs, Ship stores expenses, Sundry expenses for ships

- **Voyage expenses**

Fuel costs, Nuclear fuel cycle costs, Nuclear fuel exchange costs, Waste disposal costs, Port charges, Container-related expenses, Miscellaneous voyage expenses, Clean air costs, NSR toll

In the case of icebreaking cargo ship (20,000 DW tonnage class) sailing though the NSR led by a powerful icebreaker (Ice Class ULA: first grade type), the toll is about $100,000. **Table 4.2** shows the NSR toll [6].

Table 4.2 NSR toll

Cost component	Unit price	Number	Costs
Icebreaker fees	$3.26 / ton.displt.	28,500 ton	$92,910
Pilotage fees	$1.01 / mile	3,200 miles	$3,200
Helmsman hires	$33.33 / day	12 days	$400
Books, maps, etc.			$700
Total passage costs			$97,210

4.2 Calculation formulas for Required Freight Rate

The RFR is also calculated in the same way as in the third chapter. The items for the calculation formulas of the RFR are as follows.

- **Capital costs**
- **Operating expenses**

Crew expenses, Repair charges, Hull insurance, P&I insurance, Nuclear energy insurance, Office expenses, Lubricant costs, Ship stores expenses, Sundry expenses for ships

- **Voyage expenses**

Fuel costs, Nuclear fuel cycle costs, Nuclear fuel exchange costs, Waste disposal costs, Port charges, Container-related expenses, Miscellaneous voyage expenses, Clean air costs, NSR toll

· **Final-year special costs**

Scrap receipt, Decommissioning expenses

4.3 Calculation formulas for total cost

Total cost for carrying both electrical appliances A and B are also calculated in the same way as in the third chapter. The items for the calculation formulas of the total cost are as follows.

Distribution expenses

Freight, Premium, Interest or cost of capital for the transportation period

Stock costs

Interest or cost of capital for the storage period, Storage expenses

Sales opportunity costs

Table 4.3 Terms to calculate the total costs <NSR ships / air>

Type	Diesel			Nuclear	Air
TEU	1,200			1,400	
Knots	10	13.5	17	20	
Freight cost (f) <dollars>	95	88	83	08	1,560
Transportation period (T) <days>	33	26	22	19	4
Premium rate (i)	0.27%				0.17%
Interest (r_t, r_s)	10%				
Stock-shipment ratio (α)	20%				

Table 4.3 shows the terms to calculate the total cost. The freight cost is the cost per unit weight, which is calculated from the cost per TEU. In this study the first-year transportation cost of the nuclear ship and the diesel ship is employed to calculate the total cost (where assuming that one freight ton equals 1,000 kg per 40 cubic feet). The freight cost by air, which is 1,560 dollars per unit weight [3], is compared with the container shipping. **Table 4.3** also includes the transportation period for each shipping. Considering the disposal goods and customs formalities etc., nine days are added to the transportation period.

4.4 Calculation formulas for limit value

A limit value was calculated to determine what kinds of cargo could be carried by the diesel ship, nuclear ship, and by air. The limit value is represented by the value of the commodity and can be determined according to whether the goods to be carried are fit for the means of transportation. The function *TC*, total costs, consists of the following items.

$$TC = F + I + R_t + R_s + S + O \qquad \text{(dollars)}$$

$$= q \cdot f + i \cdot q \cdot p + r_t \cdot T / 365 \cdot q \cdot p + 1/2 \cdot r_s \cdot T / 365 \cdot q \cdot p$$
$$+ 1.25 \cdot \alpha \cdot T / 365 \cdot q \cdot p + (T - 4) / T_O \cdot q \cdot p$$

$$= q \cdot (i + r_t \cdot T/365 + r_s \cdot T/2/365 + 1.25 \cdot \alpha \cdot T/365 + (T-4)/T_O) \cdot p + q \cdot f \qquad (4.1)$$

Therefore, total costs per unit weight, *TC/w*, are shown as follows.

$$TC/w = A \cdot p + B \qquad (4.2)$$

where, $A = (i + r_t \cdot T/365 + r_s \cdot T/2/365 + 1.25 \cdot \alpha \cdot T/365 + (T-4)/T_O)$

$B = f$ (*freight*)

If the freight, premium rates, and interest are constant, the total costs can be calculated from the linear function of the value per unit weight. When the means of transportation is substituted by some other prompt delivery system such as an air transport for the conventional container shipping, i.e., the transportation period is shortened from T_1 to T_2 and the freight is increased from B_1 to B_2, the limit value is as follows.

$$TC/w = A_1 \cdot p' + B_1$$
$$TC/w = A_2 \cdot p' + B_2$$

The limit value, p', can be represented as in equation (4.3).

$$p' = (B_2 - B_1) / (A_1 - A_2) \qquad \text{(dollars/freight ton)}$$

$$= \frac{\Delta F}{i_1 - i_2 + \Delta T / 365 \cdot (r_t + r_s / 2 + 1.25 \cdot \alpha) + \Delta T / T_O} \qquad (4.3)$$

Where, $\Delta F = B_2 - B_1$, $\Delta T = T_1 - T_2$, i_1, i_2 : premium rate, r_t, r_s : interest, α : stock-shipment ratio.

4.5 Calculation results and their review

1) First-year transportation cost and RFR

Figure 4.2 shows the first-year transportation cost to carry one TEU in the first year. The first-year transportation cost for the transportation period of 19 days refers to a nuclear icebreaking container ship sailing through the NSR, and the transportation costs for the transportation periods of 23, 26, and 33 days, refer to a diesel container ship sailing through the NSR. The first-year transportation costs are higher for the nuclear ship than for the diesel ship. **Figure 4.3** shows the RFR, which is the cost of carrying one TEU during a ship's life. Similar to the first-year transportation cost, the RFR of the nuclear ship are higher than those of the diesel ship. **Figure 4.4** compares the transportation costs of the nuclear ship and the diesel ship. The declining rates from the first-year transportation costs to the RFRs is bigger for the nuclear ship compared to the diesel ship. In RFRs, there is no major difference between the two ships. Accordingly, if a ship is utilized for more than a certain period, the nuclear icebreaking container ship might be more economical than conventional NSR ships.

2) Total costs

Figures 4.5 and 4.6 show the total costs per unit weight (freight ton) in relation to the transportation period. **Figure 4.5** compares the total costs of the nuclear ship and the diesel ship carrying electrical appliance A, and **Fig. 4.6** shows the comparison of the total costs for carrying the electrical appliance B. The total costs for the transportation period of 19 days are calculated from the freight costs for the nuclear ship sailing through the NSR. Similarly, the total costs for the transportation periods of 23, 26, and 33 days are calculated from the freight costs for the diesel ship "Norilsk" when the ship's speed in the summer period is 10, 13.5, and 17 knots, respectively. In addition, the total costs for the transportation period of four days are calculated from the air freight costs. With transportation by container shipping, the total cost of the nuclear ship decrease for both electrical appliances A and B if the transportation period is short. **Figure 4.5** shows that the freight takes up 80 percent of the total costs for carrying electrical appliance A by air, and that the total costs for carrying electrical appliance A increase when the transportation period is long. As a result, the total costs tend to be higher for air transport compared to container shipping. Container shipping, therefore, becomes feasible for some goods that are usually carried by air.

Figure 4.7 shows the limit values excluding sales opportunity costs. When the means of transportation are substituted by the prompt delivery such as air transport for the conventional container shipping, the limit value is calculated from the total cost by each means of transport.

In cases where the value of the commodity is 67,000 dollars/freight ton or less, the conventional diesel ship has an advantage over the nuclear ship and air transport. In cases where the value of the commodity is between 67,000 dollars/freight ton and 840,000 dollars/freight ton, the nuclear ship has an advantage, and above 840,000 dollars/freight ton, air transport has an advantage. **Figure 4.8** shows the limit values including sales opportunity costs. In cases where the value of the commodity is between 30,000 dollars/freight ton and 385,000 dollars/freight ton, the nuclear ship has an advantage over the diesel ship and air transport. As the total costs of container shipping are high due to the amount of sales opportunity costs, the limit values of the commodity carried by nuclear ship become lower. The sales opportunity costs, which do not have a property value, are difficult to quantify equally by various transportation models. The sales opportunity costs, however, are subjective, and this will involve a choice of the means of transportation regarding prompt and optimum delivery. Therefore, the sales opportunity costs would be of particular importance when the commodities are carried by container shipping.

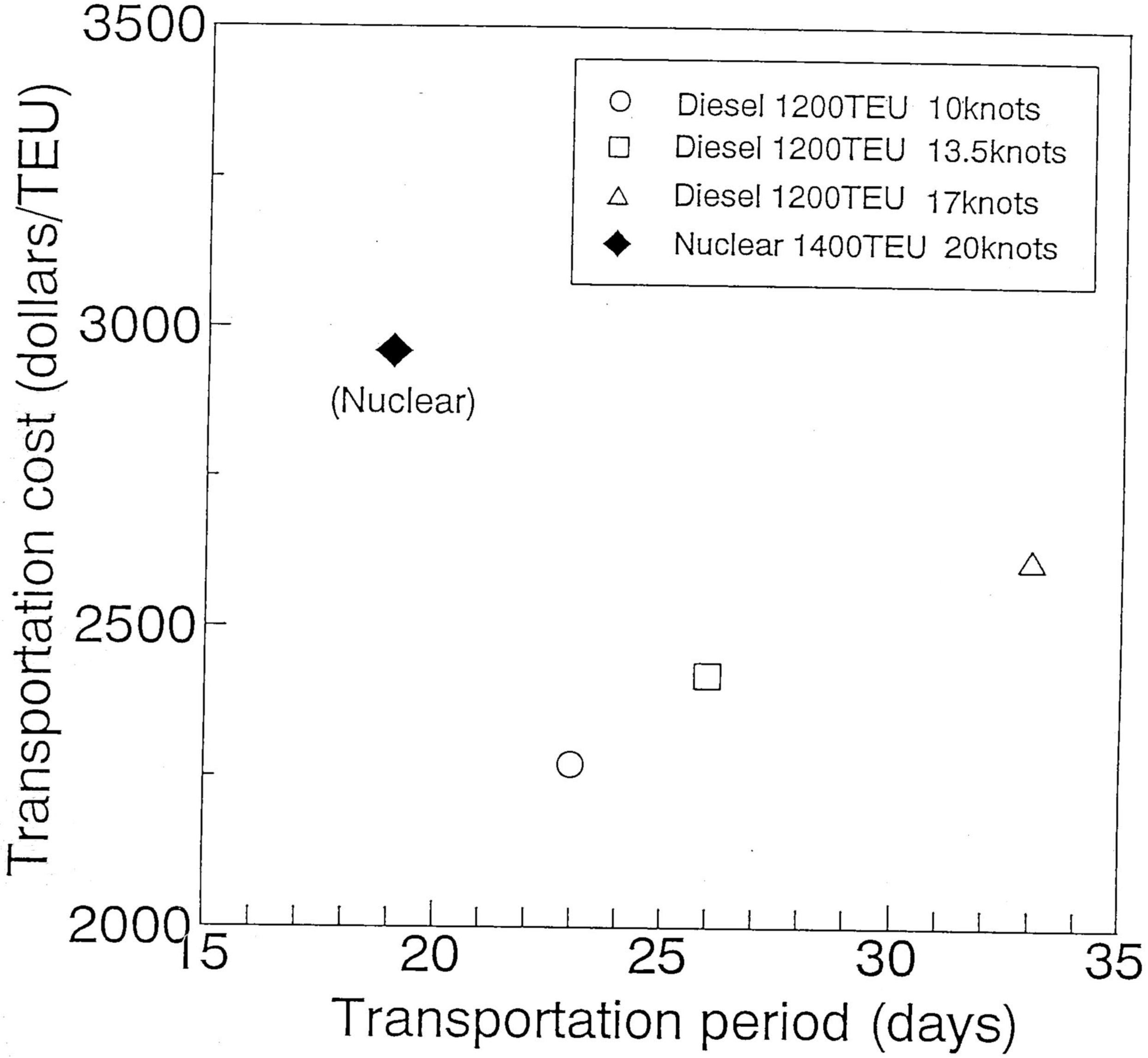


Figure 4.2 Comparison of first-year transportation costs of the NSR ships

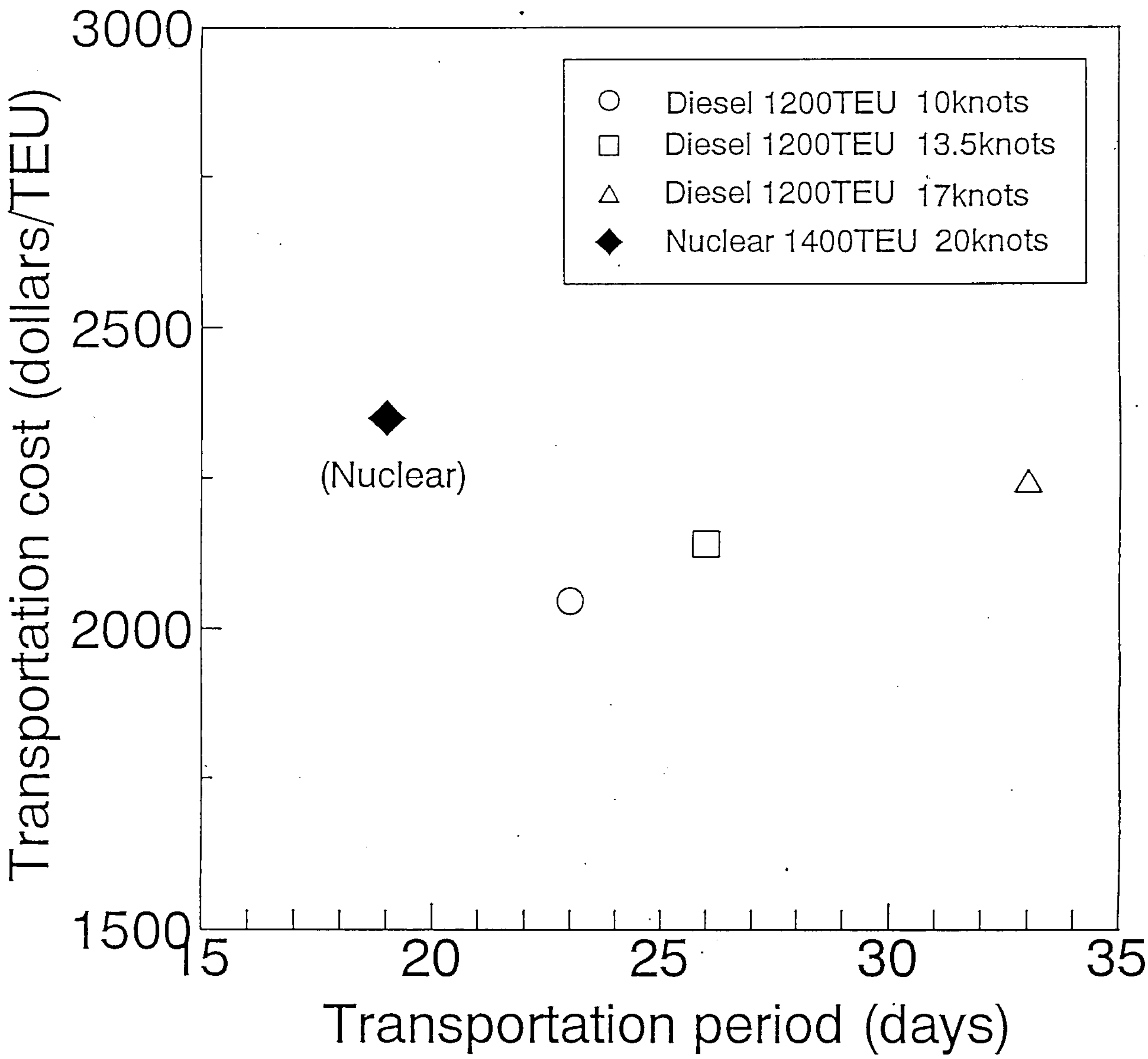


Figure 4.3 Comparison of RFRs of the NSR ships

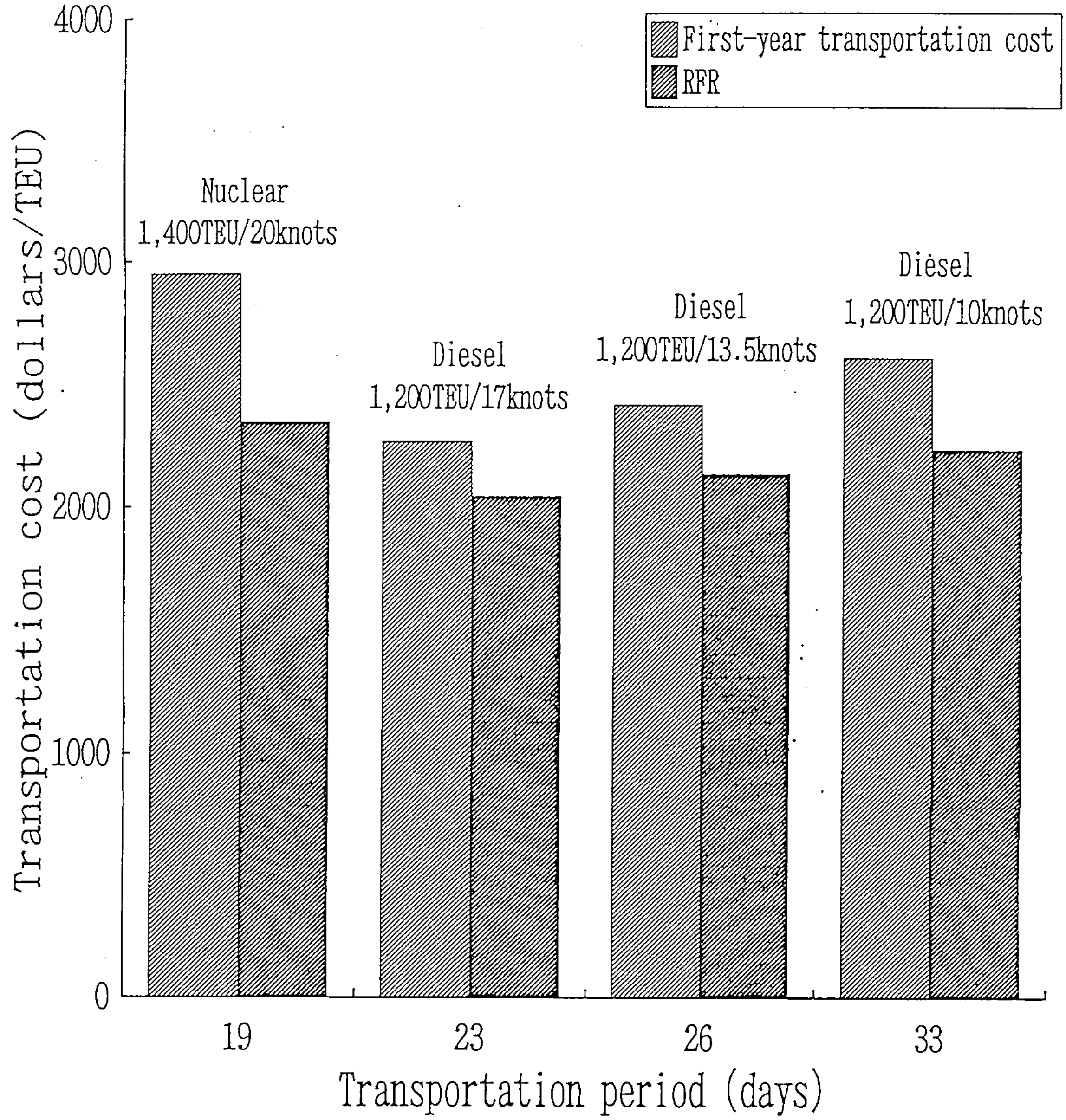


Figure 4.4 Comparison of first-year transportation costs and RFRs of the NSR ships

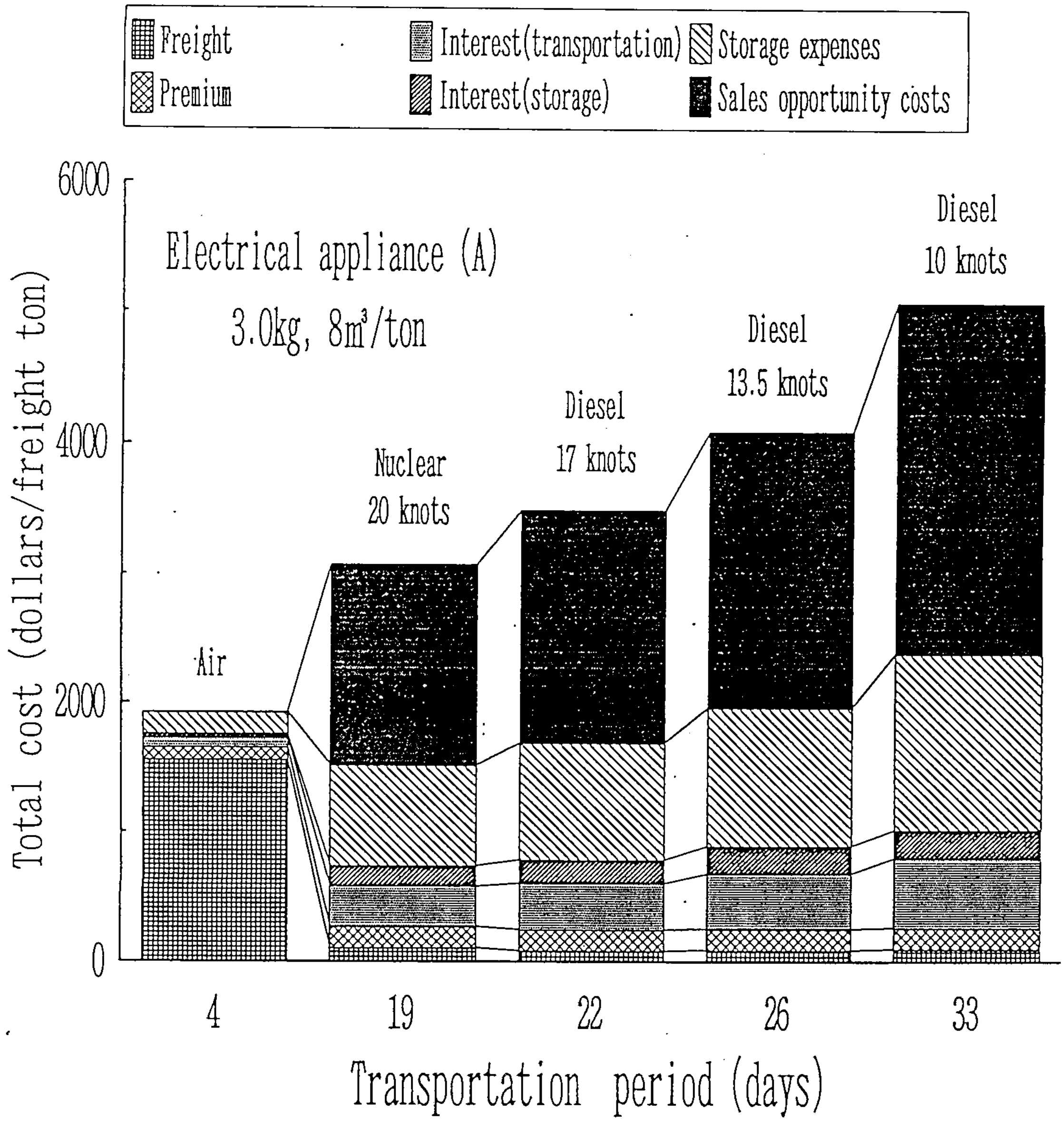


Figure 4.5 Itemization of total costs of the NSR ships carrying electrical appliance A

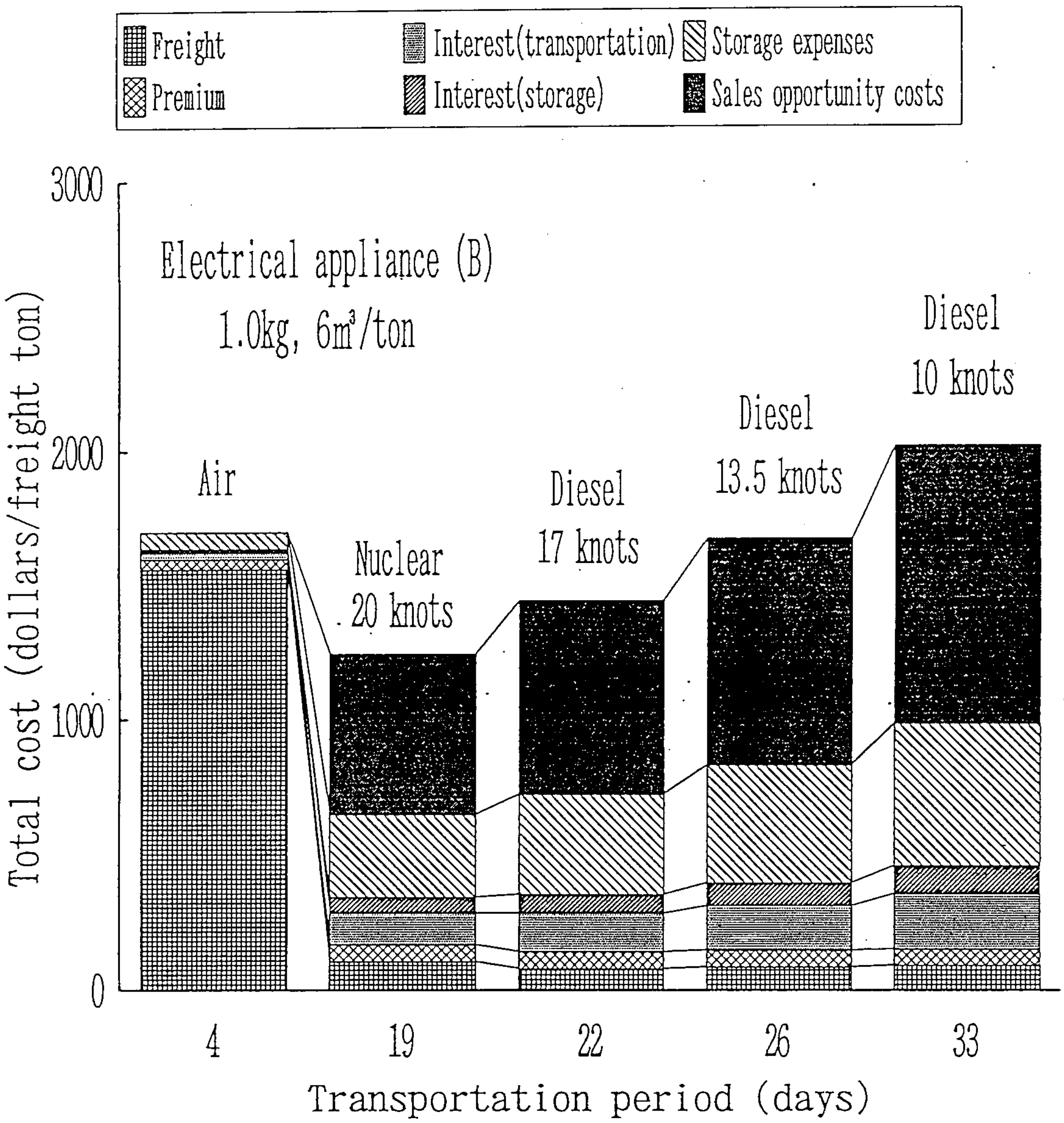


Figure 4.6 Itemization of total costs of the NSR ships carrying electrical appliance B

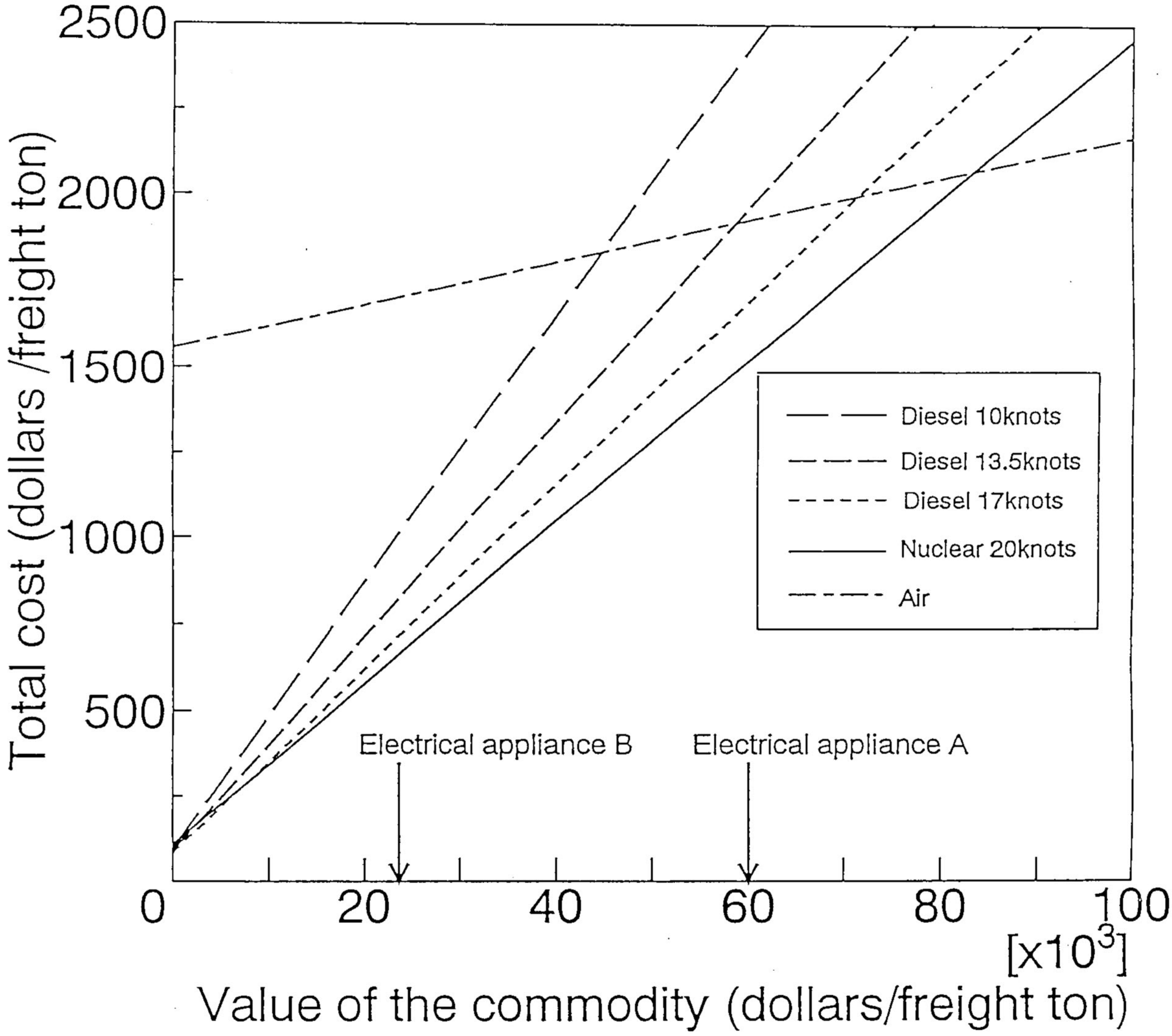


Figure 4.7 Comparison of limit values excluding sales opportunity costs

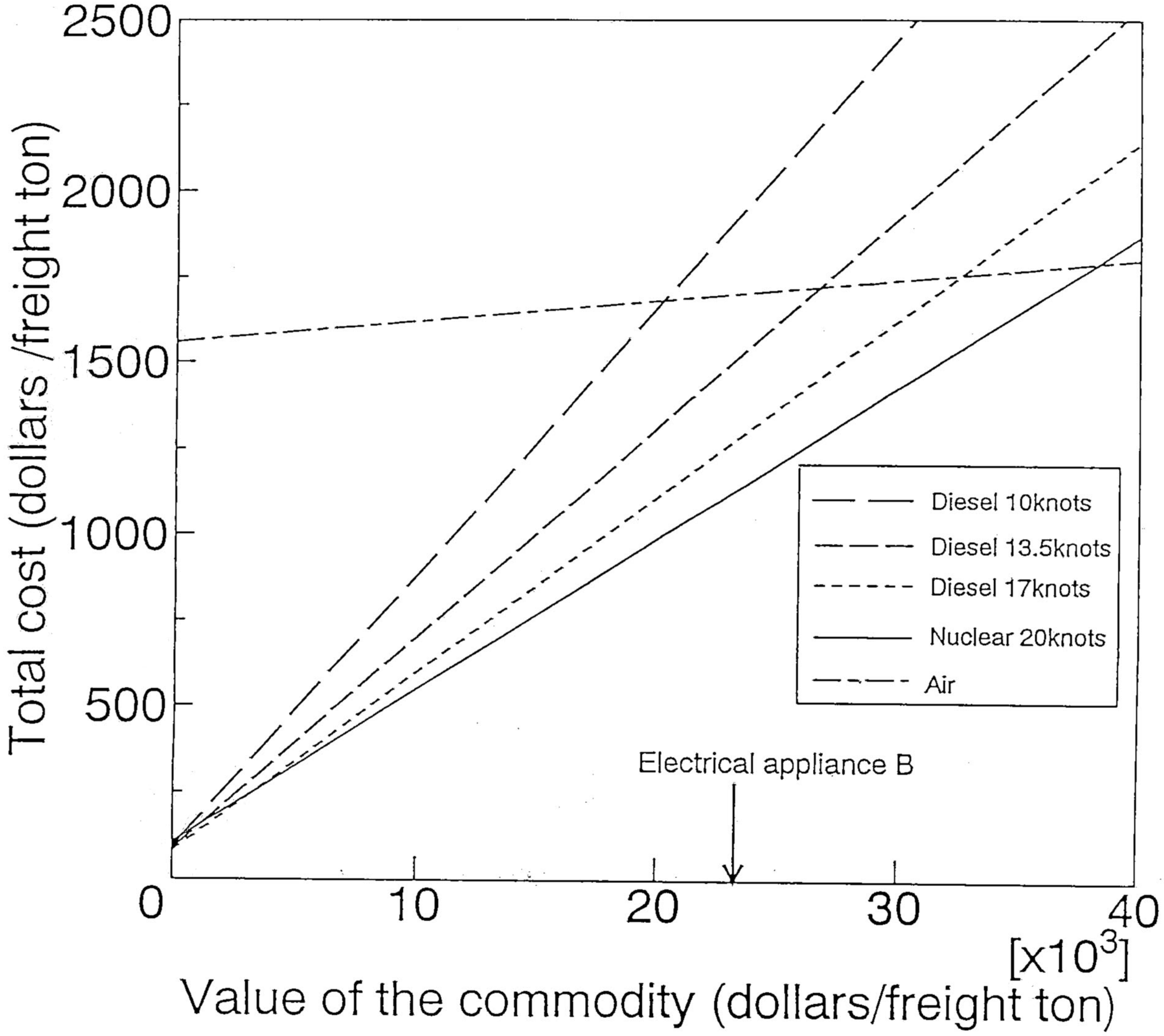


Figure 4.8 Comparison of limit values including sales opportunity costs

5. Conclusion

Using the above formulas for the nuclear icebreaking container ship and the conventional diesel container ships, we have studied the potential of a nuclear icebreaking container ship sailing through the NSR between Europe and the Far East plying the Russian coast. In this study, the economic potential of a nuclear ship as a NSR merchant ship has been examined by means of the following :

(1) A comparison of the ship-operating and container shipping expenses of the nuclear icebreaking container ship sailing through the NSR and the high-speed diesel container ships passing through the Suez Canal.

(2) A comparison of the ship-operating and container shipping expenses of the nuclear icebreaking container ship and the conventional diesel ship, both sailing through the NSR.

(3) The study and determination of the characteristics of cargo that could be carried economically by using the nuclear icebreaking container ship sailing through the NSR.

The outcome of our study is as follows.

1) First-year transportation costs and RFR

The first-year transportation costs and RFR borne by operators, which are the costs of carrying one 20-foot container, are higher for the nuclear ship sailing through the NSR than those of the diesel ships. In spite of the small-size of a nuclear icebreaking container ship, the construction costs of a nuclear ship are too high due to installing the reactor. However, the declining rate from the first-year transportation costs to the RFRs is bigger for the nuclear ship compared to those of the diesel ships. Therefore, if a ship is utilized for more than 20 years, as referred in this study, the nuclear icebreaking container ship would be economical enough compared to conventional diesel ships.

2) Total costs

In the case of container shipping, total costs, which are expenses to be paid by shippers, tend to be lower when the transportation period is shorter due to the fact that the freight has a small share in the total costs. On the other hand, comparing container shipping and air transport, the total costs of air transport are higher than those of container shipping. Container shipping would be feasible for some goods that are usually carried by air. As the limit values are calculated from the total costs, the means of transportation for prompt and optimum delivery must be optimized. For specific commodities, therefore, the NSR has an advantage over the conventional routes.

Because it can generate a large power output for a long period, a nuclear icebreaking container ship sailing through the NSR will have an advantage over a conventional diesel ship. We have now concluded that the potential for transporting cargo with a nuclear icebreaking container ship sailing through the NSR has been evaluated to be feasible against the existing container shipping and air transport. However, the above cost evaluation is based on several assumptions so it is necessary to reconsider the factors on transportation periods such as disposal of goods, custom formalities, calling port etc.. In this study the cost evaluation was made on the basis of the summer period only, also the intermodal transportation system such as transportation by sea and rail, etc. must be considered. Sales opportunity costs are included in the total costs because of the devaluation of the sales value caused by losing sales opportunities during transportation and storage period. Although the sales opportunity costs are difficult to quantify equally, sales opportunity costs are part of the standard of judgement and will involve a choice of the means of transportation regarding prompt and optimum delivery. Therefore, the sales opportunity costs would be of particular importance when the commodities are carried by container shipping.

Acknowledgements

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Appendix

A. The Results of the Calculation of a Nuclear Ship Sailing through the NSR and Diesel Ships Passing through the Suez Canal

B. The Results of the Calculation of a Nuclear Ship and a Diesel Ships Sailing through the NSR

C. The Results of the Calculation of Limit Values

Appendix A.1 First−year transportation costs

<in thousands of dollars>

	Diesel									Nuclear
Number of TEU	4,000			6,000			8,000			1,400
Ship's speed (knots)	25.0	30.0	34.0	25.0	30.0	34.2	25.0	30.0	33.5	20.0
Construction costs	112,045	149,206	200,383	163,653	198,141	249,113	194,166	234,233	273,650	209,095
Operating expenses										
Capital costs for the first year	14,107	18,785	25,229	20,604	24,946	31,364	24,446	29,490	34,453	26,325
Crew expenses	1,700	1,700	1,700	1,700	1,700	1,700	1,700	1,700	1,700	2,100
Repair charges	759	987	1,267	891	1,094	1,350	970	1,183	1,391	1,015
Hull insurance	314	418	561	458	555	698	544	656	766	1,171
P&I insurance	256	254	255	328	327	335	369	375	374	155
Nuclear energy insurance	−	−	−	−	−	−	−	−	−	936
Office expenses	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,300
Lubricant costs	780	1,811	3,622	981	1,964	3,622	1,140	2,212	3,622	−
Ship stores expenses	90	90	90	90	90	90	90	90	90	120
Sundry expenses for ships	76	76	76	76	76	76	76	76	76	76
Voyage expenses										
Fuel costs	6,867	15,943	31,886	8,632	17,287	31,886	10,033	19,473	31,886	−
Nuclear fuel cycle costs	−	−	−	−	−	−	−	−	−	6,543
Nuclear fuel exchange costs	−	−	−	−	−	−	−	−	−	258
Waste disposal costs	−	−	−	−	−	−	−	−	−	541
Port charges	1,993	2,324	2,648	2,551	2,989	3,472	2,866	3,430	3,752	1,477
Container−related expences	71,808	84,456	95,717	107,712	26,684	145,575	143,616	168,912	185,232	30,847
Miscellaneous voyage expences	176	207	235	176	207	235	176	207	227	216
Suez Canal toll	4,480	5,234	5,956	5,599	6,557	7,600	6,222	7,439	8,142	−
Clean air costs										
NOx countermeasure costs	343	797	1,594	432	864	1,594	502	974	1,594	−
SOx countermeasure costs	3,434	7,972	15,943	4,316	8,644	15,943	5,016	9,737	15,943	−
Taxes on CO_2 emissions	1,387	3,220	6,440	1,743	3,491	6,440	2,026	3,933	6,440	−
Total	112,570	148,274	197,220	160,288	201,428	253,981	203,792	253,885	299,689	76,109
First−yeatr transportation cost (dollars)	1,881	2,107	2,427	1,786	1,908	2,140	1,702	1,804	1,942	2,958

Appendix A.2 RFRs

<in millions of dollars>

	Diesel									Nuclear
Number of TEU	4,000			6,000			8,000			1,400
Ship's speed (konts)	25.0	30.0	34.0	25.0	30.0	34.2	25.0	30.0	33.5	20.0
Capital costs	117.3	156.2	209.8	171.4	207.5	260.8	203.3	245.3	286.5	218.7
Operating expenses										
Crew expenses	34	34	34	34	34	34	34	34	34	42
Repair charges	15.2	19.7	25.3	17.8	21.9	27.0	19.4	23.7	27.8	20.3
Hull insurance	3.6	4.8	6.4	5.2	6.3	7.9	6.2	7.5	8.7	13.3
P&I insurance	2.9	2.9	2.9	3.7	3.7	3.8	4.2	4.3	4.3	1.8
Nuclear energy insurance	–	–	–	–	–	–	–	–	–	10.6
Office expenses	80	80	80	80	80	80	80	80	80	86
Lubricant costs	15.6	36.2	72.4	19.6	39.3	72.4	22.8	44.2	72.4	–
Ship stores expenses	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	2.4
Sundry expenses for ships	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Voyage expenses										
Fuel costs	137.3	318.9	637.7	172.6	345.7	637.7	200.7	389.5	637.7	–
Nuclea fuel cycle costs	–	–	–	–	–	–	–	–	–	130.9
Nuclear fuel exchange costs	–	–	–	–	–	–	–	–	–	5.2
Waste disposal costs	–	–	–	–	–	–	–	–	–	10.8
Port charges	39.9	46.5	53.0	51.0	59.8	69.4	57.3	68.6	75.0	29.6
Container–related expences	1,436.2	1,689.1	1,914.3	2,154.2	2,533.7	2,871.5	2,872.3	3,378.2	3,704.6	617.5
Miscellaneous voyage expences	3.5	4.1	4.7	3.5	4.1	4.7	3.5	4.1	4.5	4.3
Suez Canal toll	89.6	104.7	119.1	112.0	131.3	152.0	124.4	148.8	162.8	–
Clean air cost										
NOx countermeasure costs	6.9	15.9	31.9	8.6	17.3	31.9	10.0	19.5	31.9	–
SOx countermeasure costs	68.7	159.4	318.9	86.3	172.9	318.9	100.3	194.7	318.9	–
Taxes on CO_2 emissions	27.7	64.4	128.8	34.9	69.8	128.8	40.5	78.7	128.8	–
Final–year special costs										
Scrap inceipt	–5.1	–6.0	–7.3	–8.1	–9.0	–10.6	–9.9	–11.1	–12.2	–1.6
Decommissioning expenses	–	–	–	–	–	–	–	–	–	15.7
Total	2,076.7	2,734.1	3,635.2	2,950.2	3,721.6	4,693.5	3,772.3	4,713.3	5,569.0	1,209.0
RFR (dollars)	1,735	1,942	2,279	1,643	1,763	1,961	1,576	1,674	1,804	2,350

Appendix A.3 Total costs for carrying electrical appliance A <in dollars/freight ton>

	Diesel									Nuclear
Number of TEU	4,000			6,000			8,000			1,400
Ship's speed (knots)	25.0	30.0	34.0	25.0	30.0	34.2	25.0	30.0	33.5	20.0
Freight	69	77	89	65	70	78	62	66	71	108
Premium	162	162	162	162	162	162	162	162	162	162
Interest of the transportation period	379	329	296	379	329	296	379	329	296	312
Interest of the storage period	189	164	149	189	164	149	189	164	149	156
Storage expenses	945	822	740	945	822	740	945	822	740	781
Sales opportunity costs	1,875	1,630	1,467	1,875	1,630	1,467	1,875	1.630	1,467	1,549
Total cost	3,619	3,184	2,901	3,615	3,177	2,892	3,612	3,173	2,885	3,068

Appendix A.4 Total costs for carrying electrical appliance B <in dollars/freight ton>

	Diesel									Nuclear
Number of TEU	4,000			6,000			8,000			1,400
Ship's speed (knots)	25.0	30.0	34.0	25.0	30.0	34.2	25.0	30.0	33.5	20.0
Freight	69	77	89	65	70	78	62	66	71	108
Premium	62	62	62	62	62	62	62	62	62	62
Interest of the transportation period	145	126	113	145	126	113	145	126	113	120
Interest of the storage period	73	63	57	73	63	57	73	63	57	60
Storage expenses	362	315	284	362	315	284	362	315	284	299
Sales opportunity costs	719	625	563	719	625	563	719	625	563	594
Total cost	1,430	1,268	1,166	1,426	1,261	1,157	1,423	1,257	1,150	1,243

Appendix B.1 First−year transportation costs

<in thousands of dollars>

	Diesel			Nuclear
Number of TEU	1,200			1,400
Ship's speed (konts)	10.0	13.5	17.0	20.0
Construction costs	56,505	56,505	56,505	209,095
Operating expenses				
Capital costs for the first year	7,114	7,114	7,114	26,325
Crew expenses	1,700	1,700	1,700	2,100
Repair charges	420	420	420	1,015
Hull insurance	158	158	158	1,171
P&I insurance	77	77	77	155
Nuclear energy insurance	−	−	−	936
Office expenses	4,000	4,000	4,000	4,000
Lubricant costs	55	187	272	−
Ship stores expenses	90	90	90	120
Sundry expenses for ships	76	76	76	76
Voyage expenses				
Fuel costs	487	1,643	2,391	−
Nuclear fuel cycle costs	−	−	−	130.9
Nuclear fuel exchange costs	−	−	−	5.2
Waste disposal costs	−	−	−	10.8
Port charges	647	647	647	1,479
Container−related expenses	14,125	18,727	23,280	30,874
Miscellanious voyage costs	647	647	647	1,479
NSR toll	1,204	1,486	1,846	−
Cleaen air costs				
NOx countermeasure costs	24.3	82.1	119.6	−
SOx countermeasure costs	243.4	821.4	1,195.7	−
Taxes on CO_2 emissions	98.3	331.8	483	−
Total	30,708	37,750	44,061	76,109
First−year transportation cost (dollars)	2,609	2,419	2,271	2,958

Appendix B.2 RFRs

<in millions of dollars>

	Diesel			Nuclear
Number of TEU	1,200			1,400
Ship's speed (konts)	10.0	13.5	17.0	20.0
Capital costs	59.2	59.2	59.2	218.7
Operating expenses				
Crew expenses	34	34	34	42
Repair charges	8.4	8.4	8.4	20.3
Hull insurance	1.8	1.8	1.8	13.3
P&I insurance	0.9	0.9	0.9	1.8
Nuclear energy insurance	—	—	—	10.6
Office expenses	80	80	80	86
Lubricant costs	1.1	3.7	5.4	—
Ship stores expenses	1.8	1.8	1.8	2.4
Sundry expenses for ships	1.5	1.5	1.5	1.5
Voyage expenses				
Fuel costs	9.7	32.9	47.8	—
Nuclear fuel cycle costs	—	—	—	130.9
Nuclear fuel exchange costs	—	—	—	5.2
Waste disposal costs	—	—	—	10.8
Port charges	12.9	12.9	12.9	29.6
Container—related expenses	282.5	374.5	465.6	617.5
Miscellanious voyage costs	3.8	3.8	3.8	4.3
NSR toll	24.1	29.7	36.9	—
Clean air costs				
NOx countermeasure costs	0.5	1.6	2.4	—
SOx countermeasure costs	4.9	16.4	23.9	—
Taxes on CO_2 emissions	2.0	6.6	9.7	—
Final—year special costs				
Scrap inceipt	−2.5	−2.5	−2.5	−1.6
Decommissioning expenses	—	—	—	15.7
Total	526.6	667.2	793.5	1,209
RFR (dollars)	2,237	2,138	2,045	2,350

Appendix B.3 Total costs for carrying electrical appliance A

<in dollars/feight ton>

	Diesel			Nuclear	Air
Number of TEU	1,200			1,400	
Ship's speed (knots)	10.0	13.5	17.0	20.0	
Freight	95	88	83	108	1,560
Premium	162	162	162	162	102
Interest of the tansportation period	543	427	362	312	66
Interest of the storage period	271	214	181	156	32
Storage expenses	1,356	1,069	904	781	164
Sales opportunity costs	2,690	2,120	1,793	1,549	0
Total cost	5,117	4,080	3,485	3,068	1,924

Appendix B.4 Total costs for electrical appliance B

<in dollars/freight ton>

	Diesel			Nuclear	Air
Number of TEU	1,200			1,400	
Ship's speed (knots)	10.0	13.5	17.0	20.0	
Freight	95	88	83	108	1,560
Premium	62	62	62	62	39
Interest of the transportation period	207	170	145	120	25
Interest of the storage period	103	85	73	60	13
Storage expenses	520	425	362	299	63
Sales opportunity costs	1,031	844	719	594	0
Total cost	2,018	1,674	1,444	1,243	1,700

Appendix C.1 Limit value (excluding sales opportunity costs)

		Diesel			Nuclear	Air
		10 knots	13.5 knots	17 knots	20 knots	
Freight (dollars/freight ton)	f	95	88	83	108	1560
Premium rate (%)	i	0.27	0.27	0.27	0.27	0.17
Interest (%)	r_t, r_s	10	10	10	10	10
Stock-shipment ratio (%)	a	20	20	20	20	20
Transportation period (days)	T	33	26	22	19	4
Incliation for the linear function of total cost	A	0.0389	0.0312	0.0268	0.0235	0.00608
Intercept for the linear function of total cost	B	95.21	88.28	82.88	107.96	1560
Comparison of the diesel ship (10knots) <in thousands of dollars / freight ton>		-	-	-	0.73391	45.021446
Comparison of the diesel ship (13.5knots) <in thousands of dollars / freight ton>		-	-	-	2.26691	59.020081
Comparison of the diesel ship (17knots) <in thousands of dollars / freight ton>		-	-	-	6.74033	71.73299
Comparison of the nuclear ship (20knots) <in thousands of dollars / freight ton>		-	-	-	-	89.98613

Appendix C.2 Limit value (including sales opportunity costs)

		Diesel			Nuclear	Air
		10 knots	13.5 knots	17 knots	20 knots	
Freight (dollars/freight ton)	f	95	88	83	108	1560
Premium rate (%)	i	0.27	0.27	0.27	0.27	0.17
Interest (%)	r_t, r_s	10	10	10	10	10
Stock-shipment ratio (%)	a	20	20	20	20	20
Transportation period (days)	T	33	26	22	19	4
Period to lose the value of commodity (days)	T_0	730	730	730	730	730
Incliation for the linear function of total cost	A	0.0786	0.0613	0.0515	0.0044	0.00608
Intercept for the linear function of total cost	B	95.21	88.28	82.88	107.96	1560
Comparison of the diesel ship (10knots) <in thousands of dollars / freight ton>		-	-	-	0.326183	20.35449
Comparison of the diesel ship (13.5knots) <in thousands of dollars / freight ton>		-	-	-	1.007516	26.82465
Comparison of the diesel ship (17knots) <in thousands of dollars / freight ton>		-	-	-	2.9957	32.75944
Comparison of the nuclear ship (20knots) <in thousands of dollars / freight ton>		-	-	-	-	38.55548

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14 August, 1996

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Dear Ms Dragland,

As promised, I have now finished with the review of Project 07.6 – "The potential of the NSR with a nuclear ice breaking container ship" – by Prof. Tomoji TAKAMASA et al. This letter contains general comments regarding the paper and it is followed by 30 pages from the paper itself, with detailed comments and corrections.

Overall, this is an excellent piece of work, which tackles the 'bold' idea of using a nuclear ship for commercial purposes. It is a pleasure to see that the project was studied from the point of view of its commercial viability, rather than its mere technical feasibility. The result is a very realistic analysis, suitably contrasted with current practice in the Europe-Japan trade route.

Although I do have some further comments and suggestions in specific parts of the paper, I chose to indicate these on the paper itself. My only general criticism refers to the fact that the paper tries to address the needs of both potential shipowners and transport managers of trading companies. In doing so, the paper becomes confusing in some parts. I believe that there is enough material there for two papers, each one addressing the needs of each group of users.

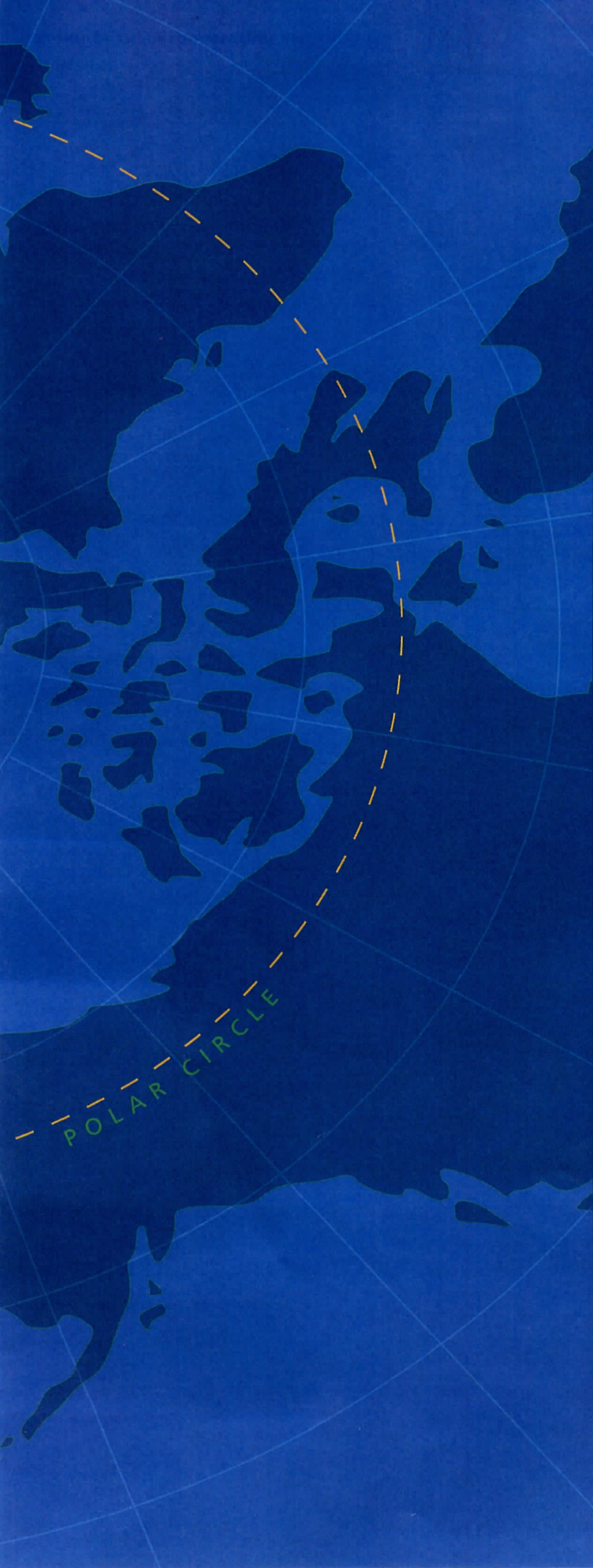
Should you have any queries regarding my suggestions, please do not hesitate to contact me. I am currently working on the second paper I am expected to review, and I will be contacting you in due course.

Once more, thank you for your assistance.

Yours sincerely

M N Tamvakis

Michael Tamvakis



The three main cooperating institutions of INSROP

Ship & Ocean Foundation (SOF), Tokyo, Japan.

SOF was established in 1975 as a non-profit organization to advance modernization and rationalization of Japan's shipbuilding and related industries, and to give assistance to non-profit organizations associated with these industries. SOF is provided with operation funds by the Sasakawa Foundation, the world's largest foundation operated with revenue from motorboat racing. An integral part of SOF, the Tsukuba Institute, carries out experimental research into ocean environment protection and ocean development.

Central Marine Research & Design Institute (CNIIMF), St. Petersburg, Russia.

CNIIMF was founded in 1929. The institute's research focus is applied and technological with four main goals: the improvment of merchant fleet efficiency; shipping safety; technical development of the merchant fleet; and design support for future fleet development. CNIIMF was a Russian state institution up to 1993, when it was converted into a stock-holding company.

The Fridtjof Nansen Institute (FNI), Lysaker, Norway.

FNI was founded in 1958 and is based at Polhøgda, the home of Fridtjof Nansen, famous Norwegian polar explorer, scientist, humanist and statesman. The institute spesializes in applied social science research, with special focus on international resource and environmental management. In addition to INSROP, the research is organized in six integrated programmes. Typical of FNI research is a multi-disciplinary approach, *entailing extensive* cooperation with other research institutions both at home and abroad. The INSROP Secretariat is located at FNI.