SHIP TRANSPORT OF CO_2

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Background to the Study

CO_2 has to be transported between capture and storage sites. Most attention has so far been on pipelines but in some come circumstances ship transport could be less costly and it could enable use of CO_2 storage reservoirs that could not be easily accessed by pipelines. The aim of this study is to assess the technology, costs and greenhouse gas emissions of ship transport systems for CO_2. The study was carried out by Mitsubishi Heavy Industries Ltd in Japan.

Study Description

The preferred method of transporting CO_2 by ship would be as a pressurised cryogenic liquid. A CO_2 ship transport system would consist of the following components:

- CO_2 liquefaction plant
- Intermediate storage tanks
- Loading facilities at a port
- Ships
- Unloading facilities

This study describes each of these components and assesses their costs and CO_2 emissions. The overall costs are compared with those of pipeline transport systems and an alternative ship transport system that uses hydrates.

Sensitivities to the following parameters are assessed:

- Transport distance
- Ship size
- Ship speed
- Pressure of the CO_2 input to the liquefaction plant

The study also considers the possibility of transporting CO_2 and LNG in the same ship. This may be of interest if CO_2 is to be stored in a region where LNG is produced.

The study is based on transport of 20,000 tonnes/day of CO_2. This is equivalent to the output from about 1,000 MW of coal-fired power plant or 2,200 MW of natural gas combined cycle plant with post combustion capture.

Results and Discussion

Status of technology
Small quantities of liquid CO_2 are already transported by ship and ships are also used to transport large quantities of other gases, such as liquefied petroleum gas (LPG) and liquefied natural gas (LNG). LNG is normally transported as a cryogenic liquid at atmospheric pressure and -162°C. LPG is usually kept in the liquid phase by elevated pressure in small ships, by a combination of pressure and low temperature in medium sized ships and by low temperature alone in large ships. CO_2 has to be transported as a pressurised low temperature liquid because it does not form a liquid at atmospheric pressure, it passes directly

from a gas to a solid when it is cooled. The recommended conditions for large scale ship transport of CO_2 are 0.7 MPa (7 bar) and -50°C.

Most LNG ships have capacities of 120-140,000m^3 and ship sizes are increasing. The largest existing pressurised refrigerated gas transport ship has a capacity of about 30,000m^3. In this study three capacities are considered for CO_2 ships: 10,000 tonnes, 30,000 tonnes and 50,000 tonnes (1 tonne of liquid CO_2 occupies slightly less than 1 m^3). Such ships could be built now without great difficulty. It may be possible to build larger ships in future if required.

CO_2 liquefaction

Most CO_2 capture processes produce gaseous CO_2 at atmospheric or slightly elevated pressure. If a CO_2 capture plant was built close to a port the CO_2 would be fed directly to a liquefaction plant, where it would be compressed, cooled using an external refrigeration circuit and then partially depressurised to provide final cooling. If the capture plant was remote from a port the CO_2 would have to be compressed and transported to the liquefaction plant by high pressure pipeline. In this case the CO_2 would not have to be compressed in the liquefaction plant, which would greatly reduce the power consumption.

In this study two liquefaction plant inlet pressures were assessed:

- 0.1 MPa, representing the output from a post combustion capture plant
- 10 MPa, representing the output from a high pressure CO_2 pipeline

Published costs of CO_2 capture normally include CO_2 compression up to a pressure of around 10 MPa. If the costs of ship transport given in this report are to be combined with published costs of CO_2 capture, the costs for inlet gas at 10 MPa should be used.

Intermediate storage and loading

This study takes into account the costs of loading and unloading of CO_2 at a port, including harbour fees. In practise CO_2 may be unloaded at offshore facilities, either for subsea geological storage or ocean storage[1]. Costs of offshore facilities would be very site specific and hence were not included in this study. This may result in higher costs, although port fees would normally not be payable for offshore unloading.

CO_2 capture is a continuous process but the cycle of ship transport is discreet, so buffer storage facilities have to be provided at the loading port. In this study CO_2 is stored as a cryogenic liquid in pressurised spherical tanks each with a capacity 20,000m^3. The amount of storage that is required depends on the shipping plan. It was assumed that no buffer storage capacity would be needed at the unloading port. This assumes that the final CO_2 storage facilities could cope with a variable CO_2 supply.

CO_2 transport ships

Three ship sizes 10,000, 30,000 and 50,000 tonnes of CO_2 were assessed. The 10,000 and 30,000 tonne ships include 4 spherical tanks and the 50,000 tonne ship includes 5 such tanks. The study also assessed two ship speeds, 15 and 18 knots (27.78 and 33.34 km/h).

CO_2 transport costs and emissions were estimated for various distances between 200 km and 12,000 km. To put these distances into context, Japan to the Persian Gulf would be about 12,000 km and Japan to Northern Australia would be about 6,000 km. Although CO_2 would probably not be transported such long distances in the near future it may be necessary in the longer term if the large potential CO_2 storage capacities in major oil and gas producing regions are to be fully exploited. LNG is already transported such distances.

[1] No judgement is made about the acceptability of CO_2 storage under international conventions.

Costs

Costs of CO_2 transport for the three different ship sizes, two liquefaction plant inlet pressures and a range of transport distances are shown in figure 1. The costs are based on a ship speed of 15 knots (27.78 km/h). The discontinuities in the curves at short distances are due to constraints on the timing of loading and unloading of ships.

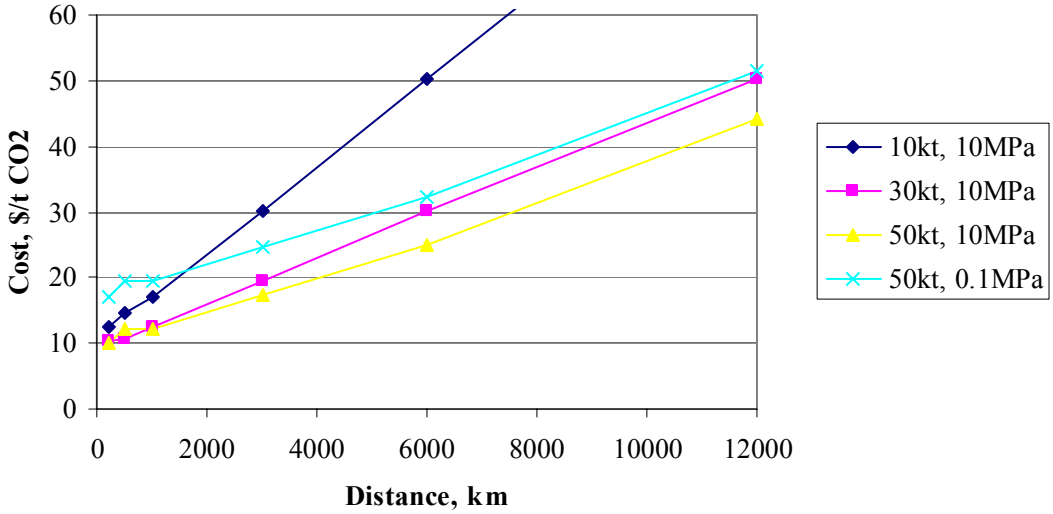

Figure 1 Sensitivity of costs of CO_2 transport to ship size and distance

Overall costs decrease substantially when the ship size increases from 10,000 to 30,000 tonnes but the cost decrease between 30,000 and 50,000 tonnes is much smaller, which may indicate that further economies of scale would be limited.

The costs of one of the cases (50,000 tonne, 15 knot ship, 10 MPa feed gas) are broken down into the main components in figure 2.

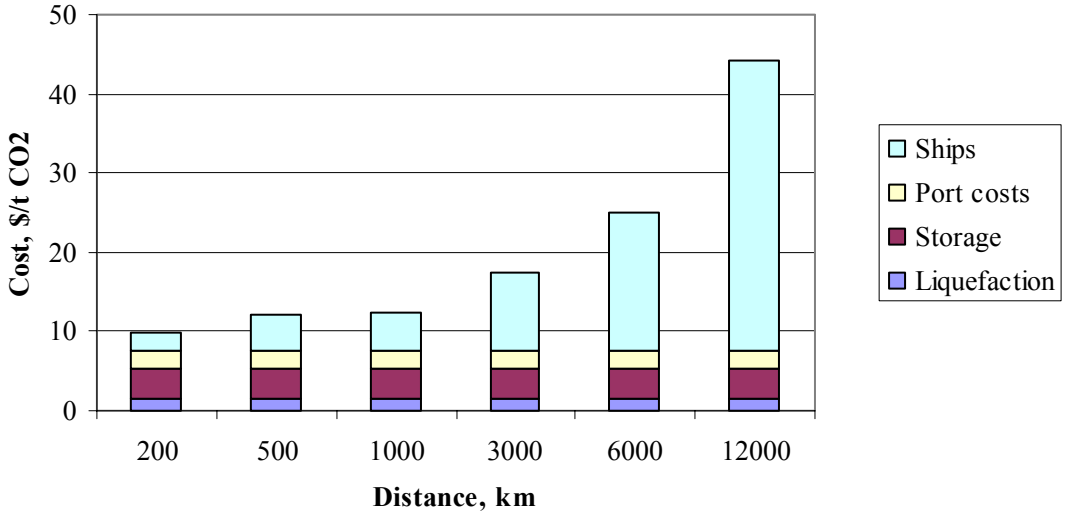

Figure 2 Breakdown of costs of CO_2 transport

It can be seen that for short distance transport, the costs of CO_2 storage and the port costs (harbour fees and loading/unloading costs) are most important but for long distance transport the costs of the ships become most important. When CO_2 is supplied at 10 MPa, as in figure 2, the costs of liquefaction are small, only about \$1.5/t CO_2. If CO_2 is supplied at 0.1 MPa the cost of liquefaction increases to \$8.7/t CO_2.

Increasing the ship speed from 15 to 18 knots slightly increases the capital cost of a ship but the overall effect is to reduce the fixed cost per tonne of CO_2 transported because more CO_2 can be transported per year in a given size of ship. However, this increase in speed increases the ship's fuel consumption per km by about 55%, resulting in higher fuel costs. Overall, the difference in ship speed affects the cost of CO_2 transport by less than 7%. The optimum ship speed depends on the transport distance and ship operating schedule.

CO_2 emissions

The overall system of ship transport results in direct and indirect emissions of CO_2.

- Boil-off from ships and shore-based storage tanks
- Ships' engines (fuel oil)
- CO_2 liquefaction (electricity)

The emissions are summarised in figure 3 for the 50,000 tonne ship, 10 MPa feed gas, 15 knot ship case.

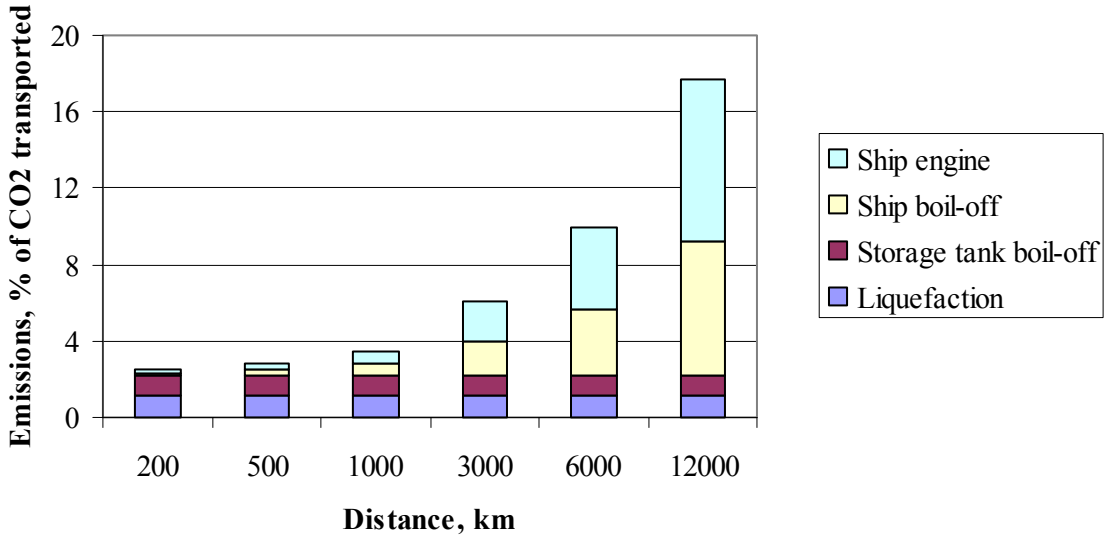

Figure 3 CO_2 emissions from ship transport

For the example shown in figure 3, total CO_2 emissions, including indirect emissions resulting from electricity consumed, are about 2.5% of the CO_2 transported for 200 km and about 18% for 12000 km. For short transport distances the emissions from liquefaction and boil-off from on-shore storage tanks are most significant and for long distance transport emissions from the ships (boil-off from the tanks and emissions from the engines) are most significant.

The emissions from liquefaction would be substantially higher if the CO_2 was supplied at atmospheric pressure. Overall emissions would be 9 percentage points higher than shown in figure 3. Increasing the ship speed from 15 to 18 knots increases the emissions from the ships' engines per tonne of CO_2 transported by about 55% but the boil-off from the ships' tanks reduces because of the faster journey. The effect on overall emissions increases with the transport distance but for example is equivalent to about 1 percent of the CO_2 transported for 3000km.

The specific CO_2 emissions are higher from smaller ships. For example, for CO_2 supplied at 10 MPa, the overall emissions from transport of CO_2 for 1000 km in 10,000 tonne ships would be 38% higher than for transport in 50,000 tonne ships. The emissions from the ships' engines would be 3.4 times higher.

Some of the CO_2 emissions from ship transport could be avoided if necessary. The CO_2 boil-off from on-shore storage tanks could be re-compressed and re-liquefied relatively easily and it may be feasible to re-liquefy the boil-off from the ships but the feasibility and costs of this were not assessed because the quantities were small except for long transport distances. Capturing and liquefying the CO_2 emitted by a ship's engine is likely to be a relatively expensive option. An alternative in the long term may be to use a low-emission energy carrier such as hydrogen to power ships.

Comparison with pipeline transport

Costs of CO_2 transport by ship are compared in figure 4 with costs of transporting the same quantity of CO_2 (20,000 t/d, 6.2 Mt/y) in onshore and offshore pipelines[2]. Ship transport is relatively expensive for short distances, because of the fixed costs of liquefaction, buffer storage and ship loading and unloading but ships become increasingly competitive for longer distances. For this quantity of CO_2, it would be cheaper to transport CO_2 by ship rather than by offshore pipeline for distances greater than about 700 km and by onshore pipeline for distances greater than about 1500 km.

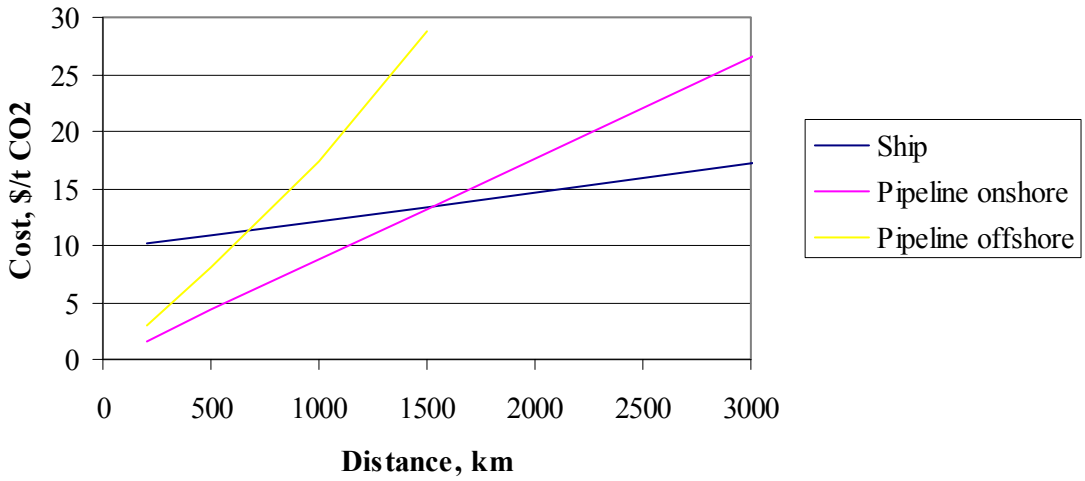

Figure 4 Comparison of costs of ship and pipeline transport of CO_2

This study did not evaluate the effects on costs of the quantity of CO_2 transported. If the same size ships were used, economies of scale may be limited mainly to saving in buffer storage and liquefaction. In contrast, there are substantial economies of scale in pipelines. Increasing the quantity of CO_2 transported by a factor of 5, to about 30 Mt/y, would approximately halve the specific cost of pipeline transport. Assuming there were no reductions in the costs of ship transport, the breakeven distance would then be about 1,500 km for offshore pipelines and over 3,000 km for onshore pipelines. Ships are therefore more competitive for longer distances and smaller quantities of CO_2.

When comparing pipelines and ships it should be borne in mind that the distances which CO_2 would have to be transported would not necessarily be the same. The transport distance for ships depends on the presence of intervening land masses. The distance for pipelines depends on geographical features, such as the need to avoid mountains and areas of high population density and environmental sensitivity. There may also be political considerations and fees if the pipeline has to transit through other countries. The pipeline costs in figure 4 do not include transit fees.

Ships have the advantage over pipelines of greater operating flexibility because they can be redirected to other routes. This aspect of ship transport was not examined in this study. Detailed site specific case studies would be required.

[2] The ship storage costs are for 50,000 tonne ships. For clarity, the ship transport cost line presented in figure 1 has been smoothed out in figure 4.

Transport of CO_2 and LNG in the same ship
There may in future be a need to transport CO_2 by ship for storage in depleted gas fields in regions where LNG is produced. It may be possible the transport CO_2 in one direction and LNG in the other using dual purpose ships. The study contractor commented on the feasibility of such ships.

LNG is normally transported at atmospheric pressure and -162°C. If it was to be transported in a pressured ship operating at 7 bar, as required for CO_2 transport, the temperature could be increased to about -130°C. However, this is still much colder than the -50°C required for CO_2. The requirement to operate at a much lower temperature would increase the cost of a CO_2 ship. Contamination of LNG and CO_2 is another significant issue. It could take a period of time in the order of days to purge CO_2 from cargo tanks before loading of LNG and vice versa. This could be a significant fraction of the total journey time, e.g. a one-way trip of 6,000 km would take less than 10 days. To change the cargo at every entrance to a port is not recommended, especially in the case of short transport distances.

If a definite need to transport CO_2 long distances arises it may be worthwhile carrying out a quantitative assessment of a complete transportation system based on dual purpose ships.

Comparison of liquid CO_2 and CO_2 hydrate transport by ship
An alternative way of transporting CO_2 by ship would be as a CO_2-hydrate. Theoretically pure CO_2 hydrates can contain almost 30% weight CO_2 with the balance being water. Such hydrates are meta-stable at atmospheric pressure and slightly sub-zero temperature. This means they could be transported in bulk without pressurisation or deep refrigeration. IEA GHG has recently published a report that includes a preliminary assessment of the feasibility and cost of ship transport of CO_2-hydrate (report PH4/26). The quantity of CO_2 transported in that study is 20,000 t/d, the same as in this study. The size of bulk carrier ship selected in the Hydrates Study was 169,400 tonnes, which is equivalent to about 50,000 tonnes of CO_2, the largest ship size considered in this study. Even though a hydrate ship would be larger, the cost of the ship per tonne of CO_2 would be lower than that of a liquid CO_2 transport ship because low temperature pressurised tanks would not be needed, although there is significant uncertainty about the cost implications of handling hydrates on a ship. However, the cost of hydrate production would be over 10 times greater than the cost of CO_2 liquefaction. Overall, when the two methods are evaluated on a consistent basis[3] it would be about $15/t cheaper to transport CO_2 as a liquid rather than as a hydrate.

Expert Group Comments

A draft version of the report was sent to various experts for review. The reviewers' comments were generally favourable but they asked for more detailed information and clarification in some areas. The comments were addressed in the final version of the report. One of the reviewers compared the costs in this study and costs in studies being carried out in Norway. For the scenarios considered by the reviewer, the costs agreed within 10%.

Major Conclusions

- CO_2 can be transported by ship as a pressurised cryogenic liquid using conventional technology, as used for LPG.

- The cost of transport would be US$10/tonne of CO_2 for 200 km, rising to US$44/t for 12,000 km, based on 50,000 tonne ships travelling at 15 knots and CO_2 supplied to the liquefaction plant at 10 MPa.

[3] The costs of hydrate transport in IEA GHG report PH4/26 are not calculated using IEA GHG's standard economic assessment criteria.

- CO_2 emissions would be equivalent to 2.5% of the CO_2 transported for 200km, rising to 18% for 12,000 km transport. This includes emissions associated with the liquefaction plant, boil-off of CO_2 from buffer storage tanks and ships and emissions from ships' engines.

- It could be cheaper to transport CO_2 by ship than by pipeline in some circumstances, particularly for longer distances. Ships would also be more flexible than pipelines, for example for transporting CO_2 to storage reservoirs which have limited lifetimes.

Recommendations

- Further work should be carried out to compare ships and pipelines for specific CO_2 capture and storage projects.

- No further work should be carried out to assess the possibility of transporting CO_2 and natural gas in the same ship unless there is a need to transport CO_2 long distances to gas producing regions.

IEA GREENHOUSE GAS R&D PROGRAMME

REPORT ON
SHIP TRANSPORT OF CO_2

June, 2004

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SUMMARY

CO_2 capture and sequestration has drawn much attention as a measure to mitigate the increasing concentration of CO_2 in the atmosphere. In the concept, CO_2 would be efficiently captured at large concentrated sources such as thermal power plants, and injected into subterranean reservoirs or into the deep ocean to be isolated from the atmosphere for a sufficiently long time period. It is preferable for many reasons that the CO_2 sequestration site is available close to the CO_2 capture site. However, realistically, transportation between both sites is necessary to a greater or lesser degree. Ship transportation is the alternative to pipeline transportation, particularly in cases where the distance across the sea is quite long, or very deep water is traversed, etc. In this study, CO_2 transportation by ship is investigated.

The marine transportation system basically consists of 1) CO_2 liquefaction system, 2) intermediate storage and loading facilities, 3) CO_2 transport ship and 4) receiving facilities. When CO_2 is transported by ship, gaseous CO_2 is fairly inconvenient as cargo, because its volume at atmospheric pressure is too large for its weight. The liquefaction process before shipping is, therefore, necessary for volume reduction. The existing technology and experiences of LPG and LNG transport could be useful references. Another requirement before shipping is the temporary storage and the loading to the ship. CO_2 is continuously captured at the plant, but the cycle of ship transport is discrete, so buffer storage facilities at the port are necessary.

In order to assess the cost of CO_2 marine transportation and the additional emissions of CO_2 from the system, case studies have been carried out. The amount of captured CO_2 from the operating plant is assumed to be 20,000 tonne / day, and the transportation distance is widely changed from 200 km to 12,000 km. Considering the amount of captured CO_2 per day and the transport distances, the ship operating schedules are planned, and then the specifications and primary costs for the liquefaction system, intermediate storage and loading facilities and CO_2 transport ships are investigated.

As results, it is found that

1) The cost of marine transportation depends on the ship size and the transport distance, dominantly. Larger ship results in lower cost/tonne-CO2, but the scale effect seems to be saturated at greater than several thousands tonne capacity. The costs described here-in-after are in case 30,000 to 50,000 tonne ships are available.

2) The cost of short distance transport (less than approx. 1,000 km) depends weakly on the distance, and is estimated to be US$17 to 20 / tonne-$CO_2$ in case that the supplied gas CO_2

before liquefaction is at atmospheric pressure. If the pressure of the CO_2 before liquefaction is 10 MPa (100 bar), the cost becomes US$10 to 13 / tonne-$CO_2$.

3) The cost of long distance transport strongly depends on the distance. The cost is estimated to be US$25 to 27 / tonne-$CO_2$ for 3,000 km transport and US$49 to 58 / tonne-$CO_2$ for 12,000 km transport, in case of atmospheric pressure CO_2 gas supply.

4) The proportion of the cost which is due to ships, in both capital and running costs, becomes higher in longer transportation.

5) The running of the liquefaction system occupies a significant part from the points of both cost and additional CO_2 emission in case of atmospheric pressure CO_2 gas supply, but not in case of use of pre-pressurized CO_2.

6) CO_2 in ship engine exhaust is one of the major sources of additional CO_2 emission. The ratio of emitted CO_2 from ship (sum of exhaust from engine and boil-off) to transported CO_2 increases proportional to the distance, and it is less when larger and/or lower speed ships are selected. When the 30,000 tonne ships are selected, 1.6 % of transported CO_2 per 1,000 km (one way distance) is emitted for 15 knots speed, and 2.1 % for 18 knots speed.

1. INTRODUCTION

The concentration of greenhouse gas in the atmosphere has been increasing and CO_2 is the main greenhouse gas emitted by human activities. Measures to mitigate the CO_2 emissions to the atmosphere are in general classified into 1) energy-saving, 2) higher efficient power generation, 3) energy shift to less CO_2 emission, 4) renewable energy, 5) nuclear, 6) CO_2 capture and sequestration, etc.

The concept of CO_2 capture and sequestration is that CO_2 would be separated from exhaust gas and collected at the large sources such as thermal power plants, steel manufacturing plants, some kinds of chemical plants, etc., and injected into the subterranean reservoirs or into the deep ocean to be isolated from the atmosphere for a sufficiently long time period.

It is preferable for many reasons that the CO_2 sequestration site is available close to the CO_2 capture site. However, realistically, transportation between both sites is necessary to a greater or lesser degree. Ship transportation is the alternative to pipeline transportation, particularly in cases where the distance across the sea is quite long, or very deep water is traversed, etc.

The International Energy Agency Greenhouse Gas R&D Programme (IEA GHG) decided to perform a study to establish the costs and feasibility of CO_2 transport by ship aiming at the use for CO_2 capture and sequestration.

Mitsubishi Heavy Industries, Ltd (MHI), Japan was awarded the study of “Ship Transport of CO_2”. MHI has a lot of construction experiences of gas transport ships. MHI started construction of LPG carriers in 1962 and LNG carriers in 1983, and has one of the largest shipyards for LNG carriers in the world. MHI has also been carrying out R&D for the capture and sequestration of CO_2 for more than 10 years.

In order to assess the cost of CO_2 marine transportation and the additional emissions of CO_2 from the system, case studies have been carried out. The amount of captured CO_2 from the operating plant is assumed to be 20,000 tonne / day, and the transportation distance is widely changed from 200 km to 12,000 km.

2. STATUS OF GAS TRANSPORT SHIPS

When transported by ships, gas is fairly inconvenient as cargo because its volume at atmospheric pressure is too large for its weight. Therefore, it is common to liquefy the gas for ship transport to reduce the volume, as experienced commercially for LNG, LPG and other chemical materials. The construction technology of large size LNG carriers and LPG carriers, and the experiences to operate those ships could be useful for the mass ship transportation of CO_2.

2.1 LNG Carriers, LPG Carriers

For the design of hull and tank structure of liquid gas transport ships, the IMO (International Maritime Organization) adopts the IGC Code (International Gas Carrier Code) in order to prevent significant secondary damage from accidental damage to ships. There are three types of tank structure for liquid gas transport ships: pressure type, low temperature type and semi-ref type. The pressure type is designed against the boiling pressure of the cargo gas under the air temperature condition. The low temperature type is on the other hand designed for sufficient low temperature to keep cargo gas as liquid under the atmospheric pressure. Low temperature type is more suitable for mass transport because the tank size restriction is not severe. The semi-ref type is designed under the combined conditions of temperature and pressure that are necessary for cargo gas to be kept as liquid. Some ships are designed to be applicable to the range of cargo conditions between air temperature/high pressure and low temperature/atmospheric pressure.

According to Lloyd's Resister Classification Survey Data (April, 2003), the numbers of LNG and LPG carriers in service or commission are:

LNG carriers … 141
LPG carriers … 1,016

The breakdowns for cargo capacity and service speed are shown in Fig.2-1 and Fig.2-2, respectively.

All of the LNG carriers are low temperature type, whose cargo condition in temperature is -162°C and capacity is larger than 10,000 m^3. The great portion is between 120,000 m^3 and 140,000 m^3. Fig.2-3 shows a picture of a 135,000 m^3 LNG carrier, for example. The number of LNG carriers under construction and on order is still large, and ship size has started to grow recently from 140,000 to 200,000 m^3.

The capacity of LPG carriers varies widely. Tank type is classified with the capacity in general:

Pressure type … smaller than 5,000 m^3
Semi-ref type …. 5,000 to 20,000 m^3
Low temp. type … larger than 20,000 m^3

Almost all of the semi-ref type of LPG carriers are smaller than 20,000 m^3, but there is a 30,000 m^3 one, 'Donau', that was built in 1985 and is the largest ship of its kind even now. The principal dimensions of 'Donau' are:

Length L_{pp} ; 183 m
Breadth B_{mld} ; 30 m
Depth D_{mld} ; 17.1 m
Cargo tank capacity; 30,207 m^3
Speed (full load) ; 16 knots

Fig.2-4 shows a picture of a 78,000 m^3 LPG carrier of low temperature type, and Fig.2-5 shows the picture of 'Donau' (http://www.meyerwerft.com/).

2.2 CO_2 Carrier

Though the size is not large, some CO_2 carriers have already been constructed. The principal dimensions of 'Coral Carbonic' are (by 'The Motor Ship', Feb.2000):

Length L_{pp} ; 74.0 m
Breadth B_{mld} ; 13.75 m
Depth D_{mld} ; 6.55 m
Draft d_{mld} ; 4.0 m
Cargo tank capacity; 1,265 m^3
No. of cargo tank ; 1
Type of cargo tank ; cylindrical

The phase diagram of CO_2 is shown in Fig.2-6. At atmospheric pressure, CO_2 is as gas phase or as solid phase depending on the temperature. Lowering the temperature at atmospheric pressure cannot by itself liquefy CO_2, only make so-called 'dry-ice'. Liquid CO_2 can only exist at a combination of low temperature and pressure well above atmospheric. A CO_2 cargo tank should therefore be the pressure type or the semi-ref type to keep CO_2 in the liquid phase. As is suggested in the status of LPG carriers, the semi-ref type would be selected for the mass transportation of CO_2.

The design point of the cargo tank would be near the triple point of CO_2. That is because the maximum tank size would be smaller and the number of necessary tanks and equipments would be greater, they would be heavier overall and would require a wider area to be set, when the design pressure is higher. Higher pressure in the tank can be resisted by a tank wall which has 1) larger curvature, 2) more thickness, 3) higher tensile strength of material. The maximum thickness and the highest tensile strength are limited from the manufacturing technologies, such as cutting, bending and welding capability of thick metal plate. Then, the necessary large curvature, that is the reciprocal of the tank radius, is designed in proportion to the pressure. That is, the maximum volume of tank is restricted in inverse proportion to the third power of pressure.

The risk of CO_2 shipping and storage is thought to be not significant in comparison with shipping and storage of LNG and LPG, because CO_2 is not combustible. However, the followings should be considered for safety;

- toxicity of air with a high concentration of CO_2
- electrostatic influence of the dry ice cloud generated during CO_2 gas release at high flow rate on the ambient fuel storage tanks

3. SYSTEM DESCRIPTION

The CO_2 marine transportation system basically consists of 1) CO_2 liquefaction system, 2) intermediate storage and loading facilities, 3) CO_2 transport ship and 4) receiving facilities in CO_2 sequestration system.

When CO_2 is transported by ship, gaseous CO_2 is fairly inconvenient as cargo, because its volume at atmospheric pressure is too large for its weight. The liquefaction process before shipping is, therefore, necessary for volume reduction. Another requirement before shipping is the temporary storage and the loading to the ship. CO_2 is continuously captured at the plant, but the cycle of ship transport is discrete, so buffer storage facilities at the port are necessary.

Fig.3-1 shows the diagram of the CO_2 marine transportation system and scope of the assessment in this study.

- Capturing CO_2 from the power plant is outside of the scope.
- Transportation of CO_2 on land from the plant to the liquefaction system is outside of the scope.
- CO_2 is liquefied and stored near the port.
- CO_2 sequestration system is outside of the scope.

4. COMPONENT STUDY

4.1 Liquefaction

Liquefaction of CO_2 is not a novel technology. Supplied CO_2 would be liquefied *via* dehydration and refrigeration processes. In this study, two cases of CO_2 pressure before liquefaction are considered. One is at atmospheric pressure supposing CO_2 gas is liquefied just after the capture process, and the other is a pre-pressurized condition at 10 MPa (100 bar) supposing the effective utilization of pressure for land transportation from the capture site to the liquefaction plant near the port.

Fig.4-1a) and b) show an example of the flow of the CO_2 liquefaction process in case of CO_2 gas supply at atmospheric pressure. It is assumed that CO_2 is captured in chemical absorption process and the impurities are already removed.

Gaseous CO_2 at the entrance of the liquefaction process is saturated with moisture. Therefore, a dehydration process is necessary at first to avoid freezing and/or hydrate generation. Almost all of the water is condensed by compression and is removed in multiple steps, and then CO_2 is made sufficiently dry with use of adsorbent like Molecular Sieves. CO_2 is then refrigerated so as to be liquefied, and cooled down furthermore with the heat of vaporization of a part of the CO_2 in a decompression process. The vaporized CO_2 is recycled. To run the liquefaction system mentioned above, cooling water and fuel for drying are necessary as well as the electric power. The following unit costs are used in this study;

- electricity cost: 5 cent/kWh
- additional CO_2 emissions due to electricity for liquefaction: 0.833kg-CO_2/kWh
- fuel cost for dehydration: US$22.73/Gcal ($5.43/GJ)
- additional CO_2 emissions due to fuel: 0.207 kg-CO_2/kcal (0.0494 kg-CO_2/kJ)
- cost of cooling water: 1.8 cent/tonne

Fig.4-2 shows an example of the flow of a CO_2 liquefaction process in case of use of pre-pressure. It is assumed dehydration has been finished. So, just refrigeration for CO_2 liquefaction and decompression to the design point are needed.

Finally, the following data are used for the case study.

1) CO_2 gas supply at atmospheric pressure

Design rate	20,000	tonne/day-CO_2
Power demand	123	kWh/tonne-CO_2 (Electrical)
Fuel demand (drying)	24	MJ/tonne-CO_2 (Fuel)

Construction cost	80,000,000	US$
Annual capital charge	11.02	% /year
Operation, maintenance	5.0	% /year
Running rate	85	% / year
Total CO_2 transport	6,205,000	tonne-CO_2 / year
Total CO_2 emission	644,000	tonne-CO_2 / year
Total cost	54,300,000	US$ / year

2) Pre-pressurized CO_2 gas supply

Design rate	20,000	tonne/day-CO_2
Power demand	14.4	kWh/tonne-CO_2 (Electrical)
Fuel demand (drying)	0	MJ/tonne-CO_2 (Fuel)
Construction cost	30,000,000	US$
Annual capital charge	11.02	% /year
Operation, maintenance	5.0	% /year
Running rate	85	% / year
Total CO_2 transport	6,205,000	tonne-CO_2 / year
Total CO_2 emission	82,000	tonne-CO_2 / year
Total cost	9,300,000	US$ / year

4.2 Intermediate Storage at Port

For the mass storage of the pressurized liquefied gas, a spherical tank with skirt support is suitable. Under the current capabilities of manufacturers, the maximum capacity of one tank which withstands the inner pressure of 0.7 MPa (7 bar) may reach approximately 20,000 m^3: the inner diameter of the tank is about 34m and the wall thickness is 50 to 60mm. The structural material is high tensile steel proofing against low temperature as used for LPG tanks. Heat absorption from outside is restrained with thermal insulating material on the wall.

The following data are used for the case study. CO_2 emission from the system is evaluated from the boil-off rate. In order to reduce the CO_2 emission, re-liquefaction of the boil-off CO_2 might be possible technically, but it would be more realistic at first to pursue the performance of the heat insulation of the tanks.

Cargo condition	7 bar, -50°C	
Storage capacity (nominal)	20,000	tonne / tank
(nominal)	18,500	m^3 / tank
Tank volume	20,500	m^3 / tank
No. of tanks	1 + spare tanks	for ship size of 10,000 tonne
	2 + spare tanks	for ship size of 30,000 tonne
	3 + spare tanks	for ship size of 50,000 tonne
No. of spare tanks	2	
Construction cost	30,000,000	US$ / tank
Annual capital charge	11.02	% / year
Operation, maintenance	5.0	% / year
CO_2 emission	0.2	% of capacity / day

4.3 Loading/Unloading Facilities

Loading facilities from the storage tank on land to the ship would be the loading arm type, and pumps are located at the port. Unloading depends on the receiving facilities in the sequestration system, however pumps in the cargo tanks of the ship would be used.

The following data are used for the case study. The treatment of 20,000 tonne/day is quite a large amount, so the operating cost including frequent maintenance should be estimated enough. CO_2 emission is assumed to be negligible.

No. of loading arms	6 * 2 sets (loading and unloading each)	
No. of return gas arms	2 * 2 sets (loading and unloading each)	
Construction cost	8,000,000	US$ (in total)
Annual capital charge	11.02	% / year
Operation, maintenance	2,000,000	US$ / year (in total)

4.4 CO_2 Transport Ship

CO_2 transport ships considered in this study are much larger than existing ones. It may be possible to construct very large ships in future, if necessary, but here the maximum capacity is assumed to be 50,000 tonne that seems within the range that can be constructed with current technology of shipbuilding.

The three ship sizes (10,000 tonne, 30,000 tonne and 50,000 tonne) and two service speeds (15 knots and 18 knots for full load condition) are applied for the case study. Based on the initial designing scheme of shipbuilding designers, principal dimensions of the CO_2 ships are planned as shown in Table 4-1. Fig.4-3 shows the outline of CO_2 ship for 30,000 tonne capacity and 15 knots service speed, for example.

The following data are used for the case study. CO_2 emission is due to the fuel consumption and the boil-off from cargo. Higher speed ships can offer lower capital costs because of a reduction of the necessary numbers of ships, and less boil-off CO_2. But it is a trade-off with higher running costs and more CO_2 exhaust due to the greater fuel consumptions. The relations between ship speeds and fuel consumptions for each ship size are evaluated based on the shipbuilding designers' scheme. It is assumed that diesel engines burning heavy fuel oil "C" are applied and 3.19 tonne-CO_2 emissions and US$182 cost per tonne-fuel are used for the estimation. Re-liquefaction of boil-off gas would be possible, but is not considered in this study because the CO_2 in exhaust of the engine is dominant.

1) 10,000 tonne, 15 knots

Construction cost	34,000,000	US$ / ship
Running rate	85	% / year
Annual capital charge	11.02	% / year
Crew, Insurance, Maintenance	5.0	% / year
Harbor fee	2 * 21,690	US$ / cycle / ship
Fuel cost	4,770	US$ / day / ship
CO_2 emission	0.2	% of capacity / day (boil-off)
	84	tonne-CO_2 / day / ship (in exhaust of engine)

2) 10,000 tonne, 18 knots

Construction cost	35,000,000	US$ / ship
Running rate	85	% / year
Annual capital charge	11.02	% / year
Crew, Insurance, Maintenance	5.0	% / year
Harbor fee	2 * 21,690	US$ / cycle / ship
Fuel cost	9,150	US$ / day / ship
CO_2 emission	0.2	% of capacity / day (boil-off)
	161	tonne-CO_2 / day / ship (in exhaust of engine)

3) 30,000 tonne, 15 knots

Construction cost	58,000,000	US$ / ship
Running rate	85	% / year

Annual capital charge	11.02	% / year
Crew, Insurance, Maintenance	5.0	% / year
Harbor fee	2 * 34,270	US$ / cycle / ship
Fuel cost	6,080	US$ / day / ship
CO_2 emission	0.2	% of capacity / day (boil-off)
	107	tonne-CO_2 / day / ship (in exhaust of engine)

4) 30,000 tonne, 18 knots

Construction cost	60,000,000	US$ / ship
Running rate	85	% / year
Annual capital charge	11.02	% / year
Crew, Insurance, Maintenance	5.0	% / year
Harbor fee	2 * 34,270	US$ / cycle / ship
Fuel cost	11,480	US$ / day / ship
CO_2 emission	0.2	% of capacity / day (boil-off)
	201	tonne-CO_2 / day / ship (in exhaust of engine)

5) 50,000 tonne, 15 knots

Construction cost	82,000,000	US$ / ship
Running rate	85	% / year
Annual capital charge	11.02	% / year
Crew, Insurance, Maintenance	5.0	% / year
Harbor fee	2 * 45,850	US$ / cycle / ship
Fuel cost	6,920	US$ / day / ship
CO_2 emission	0.2	% of capacity / day (boil-off)
	121	tonne-CO_2 / day / ship (in exhaust of engine)

6) 50,000 tonne, 18 knots

Construction cost	85,000,000	US$ / ship
Running rate	85	% / year
Annual capital charge	11.02	% / year
Crew, Insurance, Maintenance	5.0	% / year
Harbor fee	2 * 45,850	US$ / cycle / ship
Fuel cost	12,700	US$ / day / ship
CO_2 emission	0.2	% of capacity / day (boil-off)
	223	tonne-CO_2 / day / ship (in exhaust of engine)

Strictly speaking, the ship dimensions vary with the designed transportation distance because of the fuel tank capacity, but here, the effect of differences in the fuel tank capacity on the cost and fuel consumption is neglected.

5. PARAMETRIC STUDY

5.1 Parameters

In order to assess the cost and additional emissions from the system, case studies are performed parametrically. The following conditions are considered:

Transport distance (one way) ; 200km, 500km, 1,000km, 3,000km, 6,000km, 12,000km
Ship capacity ; 10,000 tonne, 30,000 tonne, 50,000 tonne
Ship speed (full load condition - ballast condition) ; 15-16 knots, 18-19 knots
Gas CO_2 condition before liquefaction ; atmospheric, 100 bar

Totally, 72 cases' study is performed (Table 5-1).

5.2 Ship Operating Schedule

In order to determine the number of ships and intermediate storage tanks, ship operating schedule is planned considering the transport distance, ship capacity and ship speed. It is assumed in this study that the loading and unloading time is 8 hours in daytime. All results are shown in the Appendix.

For example, one round trip in the case of 200 km transport by 10,000 tonne ships of 15-16 knots, shall be:

Day 1	08:00hrs	start loading
	16:00hrs	depart from loading site
Day 2	00:00hrs	arrive at unloading site
	08:00hrs	start unloading
	16:00hrs	depart from unloading site
	23:00hrs	arrive at loading site

The cycle then repeats commencing with 08:00hrs loading on the next day. Waiting time for the start of loading/unloading occupies a significant part in such a short distance transport. 4 ships, 1 storage tank for regular use and 2 storage tanks for spare are required.

For one more example for longer transport, one round trip in the case of 1,000 km transport by 30,000 tonne ships of 15-16 knots, shall be:

Day 1	08:00hrs	start loading
	16:00hrs	depart from loading site

Day 3 04:00hrs arrive at unloading site
08:00hrs start unloading
16:00hrs depart from unloading site
Day 5 03:00hrs arrive at loading site

It takes 4 days for one round trip. 3 ships, 2 storage tanks for regular use and 2 storage tanks for spare are required.

In case of LNG carriers, the reliability is ensured with the periodical inspection in dock every 2 or 3 years. It takes about 2 weeks. The running rate of CO_2 carriers would be determined from the running rate of the plant on land, such as the thermal power plant, therefore, the CO_2 carriers could be inspected periodically with no spare ones.

5.3 Cost Estimation

Conclusions of cost estimation for all parametric cases are shown in Tables 5-2 and 5-3, and are summarized in Fig.5-1. For deeper understanding, the construction cost (initial cost) and its breakdown for each parametric study are shown in Fig.5-2 to 5-7, and the cost per year (proportional to the cost per tonne-CO_2 in this study) and its breakdown are shown graphically in Fig.5-8 to 5-13.

The total cost of marine transportation of CO_2 depends on the ship size and the transport distance, dominantly. Larger ships results in lower costs per tonne-CO_2, but the scale effect seems to be saturated at greater than several thousands tonne capacity. The costs described here-in-after are in case 30,000 to 50,000 tonne ships are available.

The cost of short distance transport (less than approx. 1,000 km) depends weakly on the distance, and is estimated to be US$17 to 20 / tonne-$CO_2$ in the case that the supplied CO_2 gas before liquefaction is at atmospheric pressure. The running cost of the liquefaction system accounts for a significant portion, and the numbers of ships and storage tanks are not so influential.

If the pressure of supplied CO_2 before liquefaction could be utilized effectively, the cost becomes US$10 to 13 / tonne-$CO_2$. It is quite notable.

In the shorter distance transport, it seems that more efficient planning could be done with the optimization of ship size, speed and storage tank size. Usage of night time for loading and unloading would be also effective to the cost reduction.

The cost of long distance transport strongly depends on the distance. The cost is estimated to be US$25 to 27 / tonne-$CO_2$ for 3,000 km transport and US$49 to 58 / tonne-$CO_2$ for 12,000 km transport, in case of atmospheric pressure CO_2 gas supply.

The proportion of cost due to ships in both capital and running costs becomes higher in longer transportation. In case of no-use of pre-pressure, 15 to 25% of the cost is due to ships for the short distance transport, but over 70% for 12,000km transport because so many ships are needed. It is emphasized in the case of the use of pre-pressure of CO_2.

The difference of ship design speed between 15 knots and 18 knots has a fairly small effect on the cost per tonne-CO_2.

The proportion of cost due to intermediate storage or harbor fees is almost the same as that due to ships for the short distance transport, and decreases relatively in longer transport. The loading and unloading cost is small in this study's results.

5.4 Additional CO_2 Emission

Estimated additional emissions of CO_2 from the system are shown in Tables 5-4 and 5-5, and are summarized in Fig.5-14, where the percentages of CO_2 emission from the system to the total CO_2 supplied to the liquefaction plant are shown. For deeper understanding, the total CO_2 emission from the system per year and its breakdown for each parametric study are shown graphically in Fig.5-15 to 5-20.

Major sources of additional CO_2 emission are power supply for CO_2 liquefaction and exhaust of ship engines. Boil-off CO_2 from intermediate storage tanks and ship tanks are not so significant.

CO_2 emission due to liquefaction corresponds to 10 % of transported CO_2 in case of no-use of pre-pressure, and 1.2 % in case of use of pre-pressure. It seems valuable to investigate the optimization of CO_2 compression in total transportation system from capturing site.

CO_2 emission from ships, that is the sum of exhaust from the engine and boil-off gas, is proportional to the transportation distance, and is less when larger and lower speed ships are selected. In the case of 30,000 tonne ships, 1.6 % of transported CO_2 per 1,000 km (one way distance) is emitted for 15 knots speed, and 2.1 % for 18 knots speed.

5.5 Influence of some other parameters

Fig.5-21and Fig.5-22 show the comparison of cost when the electricity cost for liquefaction is 9.1 cent/kWh instead of 5.0 in case that 30,000 tonne ships of 15 knots speed are applied. Needless to say, the capital cost is not influenced, and the sensitivity of the electricity cost to the total cost depends on how high is the share of the running cost of liquefaction. The total cost increases by US$4 / tonne-$CO_2$ in case of atmospheric pressure CO_2 gas supply, and by less than US$1 / tonne-$CO_2$ in case of use of pre-pressure.

Fig.5-23 to 5-29 show the comparison of costs when intermediate storage tanks are needed also at the receiving facilities. It is assumed that the size of tanks is the same as the loading side ones, and there are no spare tanks. The total cost increases by US$2 / tonne-$CO_2$ due to mainly the increase of the construction cost of unloading tanks.

6. REMARKS

Since there exist commercial CO_2 liquefaction facilities, CO_2 storage tanks on shore, and CO_2 transport ships, it is not novel to construct the CO_2 marine transportation system. However, there have not been the demands for mass transportation as assumed for CO_2 sequestration, so entirely new designs would be necessary for a large scale up. The existing technologies and experiences of LPG and LNG transport could be useful references.

Regarding CO_2 storage tanks, it is assumed in this study that 60 mm thick plate of 9% nickel steel for low temperature could be used in the near future for manufacturing, and then up to 20,000 m^3 storage tank is likely possible. More details should be investigated considering the technological state, the availability of land, etc. at the location.

CO_2 transport ships would be of similar design to the semi-ref type of LPG carrier. The maximum capacity of existing semi-ref LPG carriers is about 30,000 m^3. Therefore, it is promising to build CO_2 ship of 30,000 tonne or 50,000 tonne at the most without great difficulties. For building larger ships, the following studies will be needed;

- Possible size of CO_2 tank on board
  Since the tank is a pressurized vessel, investigations are needed on the allowable thickness of plate from the point of view of manufacturing and on the high tensile material for low temperature use, etc.

- Number of CO_2 tanks and layout
  There exists a proper range of the proportion of ship length to breadth. When CO_2 tanks on board form one line, the breadth of the ship would be to some extent larger than the tank diameter and the number of tanks might be up to 8. If more than 2 lines of CO_2 tanks are considered, much fundamental design work would be necessary.

- Limit of draft from port depth
  Large ships needs in general large draft in the full load conditions, so port depth is a limitation. It should be taken into account that the density of liquid CO_2 is higher than other liquefied gases or oil.

Finally, some technical comments are made to the conceptual idea of transport of CO_2 and natural gas in the same type of ship. The idea is intended to make efficient use of one ship in both directions.

LNG is liquefied natural gas whose main component is methane. The boiling temperature of methane at atmospheric pressure is -162°C, and the critical temperature is -83°C, above

which the gas cannot be liquefied however high pressure is applied. Very low temperature is required anyway, and the design point of LNG carriers is in general -162°C at slightly higher than atmospheric pressure.

On the other hand, the triple point of CO_2 is about -57°C and 5.3 bar. CO_2 condition would become unstable at the vicinity of the triple point, so the design point of CO_2 carriers is set in this study at -50°C and 7.0 bar.

If the ship is designed to transport CO_2 and LNG using the same cargo tanks, both low enough temperature for natural gas as liquid phase and high enough pressure for CO_2 as liquid phase are required; -130°C and 7.0 bar, for example. The tanks would be over-specified for each cargo gas, and the merit of common use would be lost at least to some degree.

In addition, the contamination of LNG and CO_2 should be avoided to an allowable degree. It takes time in the order of days for purging CO_2 from cargo tanks before the loading of LNG, and *vice versa*. Therefore, to change cargo gas at every entrance to a port is to be avoided, especially in case of short distance shuttle service. Using different ships is recommended.

Table 4-1 Principal dimensions of CO_2 carriers

Cargo Weight	10,000 t	10,000 t	30,000 t	30,000 t	50,000 t	50,000 t
Speed(Full Load)	15 kn	18 kn	15 kn	18 kn	15 kn	18 kn
Speed(Ballast)	16 kn	19 kn	16 kn	19 kn	16 kn	19 kn
Lpp	116.0 m	116.0 m	156.0 m	156.0 m	220.2 m	220.2 m
Bmld	24.3 m	24.3 m	34.1 m	34.1 m	38.8 m	38.8 m
Dmld	12.8 m	12.8 m	17.1 m	17.1 m	18.5 m	18.5 m
dmld(draught, moulded)	9.5 m	9.5 m	11.0 m	11.0 m	11.0 m	11.0 m
Number of CO2 tanks	4	4	4	4	5	5
Inside Diameter of CO2 tank	16.5 m	16.5 m	23.8 m	23.8 m	26.1 m	26.1 m
Material of CO2 tank	Steels for low temperature service(For example ;9% Ni Steel)					

(1) L_{pp} ; length between perpendiculars, which is the distance measured along the summer load waterplane from the after to the fore perpendicular.

(2) B_{mld} ; moulded breadth, which is the greatest distance between the inside of plating on the two sides of the ship.

(3) D_{mld} ; moulded depth, which is the vertical distance from the underside of the uppermost continuous deck plating at the ship's side to the top of the inner keel plate.

(4) d_{mld} ; moulded draught, which is the draught using the moulded base line.

Table 5-1 Case study conditions

DISTANCE	SHIP SIZE	SHIP SPEED		Pressure of CO2 before liquefaction	DISTANCE	SHIP SIZE	SHIP SPEED		Pressure of CO2 before liquefaction
km	ton	(Full Load) kn	(Ballast) kn		km	ton	(Full Load) kn	(Ballast) kn	
200	10000	15	16	atmospheric pressure 'post capture'	200	10000	15	16	100 bar 'pre-pressurized'
200	30000				200	30000			
200	50000				200	50000			
500	10000				500	10000			
500	30000				500	30000			
500	50000				500	50000			
1000	10000				1000	10000			
1000	30000				1000	30000			
1000	50000				1000	50000			
3000	10000				3000	10000			
3000	30000				3000	30000			
3000	50000				3000	50000			
6000	10000				6000	10000			
6000	30000				6000	30000			
6000	50000				6000	50000			
12000	10000				12000	10000			
12000	30000				12000	30000			
12000	50000				12000	50000			
200	10000	18	19		200	10000	18	19	
200	30000				200	30000			
200	50000				200	50000			
500	10000				500	10000			
500	30000				500	30000			
500	50000				500	50000			
1000	10000				1000	10000			
1000	30000				1000	30000			
1000	50000				1000	50000			
3000	10000				3000	10000			
3000	30000				3000	30000			
3000	50000				3000	50000			
6000	10000				6000	10000			
6000	30000				6000	30000			
6000	50000				6000	50000			
12000	10000				12000	10000			
12000	30000				12000	30000			
12000	50000				12000	50000			

Table 5-2 Total cost of CO_2 marine transportation

CO2 pressure before liquefaction	DISTANCE	SHIP										Liquefaction System				CO2 tank				Loading/Unloading				TOTAL				
		SHIP SIZE	SHIP SPEED		Number of Ship	Number of service	Construction	Capital Cost	Running Cost		Harbor Fee	Construction	Capital Cost	Running Cost	Number of tanks	Construction	Capital Cost	Running Cost		Construction	Capital Cost	Running Cost		Construction	Capital Cost	Running Cost & Harbour Fee	Total amount of CO2	[Capitan,Running Cost & Harbour Fee] / year
						Running rate 85% / year			Crew, Insurance, Maintenance	Fuel																		
	km	ton	(Full Load) kn	(Ballast) kn		Number/ship/ year	Million US$	Million US$	Million US$	Million US$	Million US$	Million US$	Million US$	Million US$		Million US$	Million US$	Million US$		Million US$	Million US$	Million US$		Million US$	Million US$	Million US$	ton/year	US$/tCO2
atmospheric pressure	200	10000	15	16	4	155.1	136.0	15.0	6.8	1.8	26.9	80.0	8.8	45.5	3	90.0	9.9	4.5		8.0	0.9	2.0		314.0	34.6	87.5	6205000	19.7
	500				6	103.4	204.0	22.5	10.2	4.3	26.9	80.0	8.8	45.5	3	90.0	9.9	4.5		8.0	0.9	2.0		382.0	42.1	93.4	6205000	21.8
	1000				8	77.6	272.0	30.0	13.6	8.6	26.9	80.0	8.8	45.5	3	90.0	9.9	4.5		8.0	0.9	2.0		450.0	49.6	101.1	6205000	24.3
	3000				20	31.0	680.0	74.9	34.0	25.9	26.9	80.0	8.8	45.5	3	90.0	9.9	4.5		8.0	0.9	2.0		858.0	94.6	138.8	6205000	37.6
	6000				38	16.3	1292.0	142.4	64.6	51.7	26.9	80.0	8.8	45.5	3	90.0	9.9	4.5		8.0	0.9	2.0		1470.0	162.0	195.1	6205000	57.6
	12000				74	8.4	2516.0	277.3	125.8	103.2	26.9	80.0	8.8	45.5	3	90.0	9.9	4.5		8.0	0.9	2.0		2694.0	296.9	307.9	6205000	97.5
	200	30000			2	103.4	116.0	12.8	5.8	0.8	14.2	80.0	8.8	45.5	4	120.0	13.2	6.0		8.0	0.9	2.0		324.0	35.7	74.2	6205000	17.7
	500				2	103.4	116.0	12.8	5.8	1.8	14.2	80.0	8.8	45.5	4	120.0	13.2	6.0		8.0	0.9	2.0		324.0	35.7	75.3	6205000	17.9
	1000				3	68.9	174.0	19.2	8.7	3.7	14.2	80.0	8.8	45.5	4	120.0	13.2	6.0		8.0	0.9	2.0		382.0	42.1	80.0	6205000	19.7
	3000				7	29.5	406.0	44.7	20.3	11.0	14.2	80.0	8.8	45.5	4	120.0	13.2	6.0		8.0	0.9	2.0		614.0	67.7	98.9	6205000	26.9
	6000				13	15.9	754.0	83.1	37.7	22.0	14.2	80.0	8.8	45.5	4	120.0	13.2	6.0		8.0	0.9	2.0		962.0	106.0	127.3	6205000	37.6
	12000				24	8.6	1392.0	153.4	69.6	43.8	14.2	80.0	8.8	45.5	4	120.0	13.2	6.0		8.0	0.9	2.0		1600.0	176.3	181.1	6205000	57.6
	200	50000			1	124.1	82.0	9.0	4.1	0.5	11.4	80.0	8.8	45.5	5	150.0	16.5	7.5		8.0	0.9	2.0		320.0	35.3	71.0	6205000	17.1
	500				2	62.1	164.0	18.1	8.2	1.3	11.4	80.0	8.8	45.5	5	150.0	16.5	7.5		8.0	0.9	2.0		402.0	44.3	75.8	6205000	19.4
	1000				2	62.1	164.0	18.1	8.2	2.5	11.4	80.0	8.8	45.5	5	150.0	16.5	7.5		8.0	0.9	2.0		402.0	44.3	77.0	6205000	19.6
	3000				4	31.0	328.0	36.1	16.4	7.5	11.4	80.0	8.8	45.5	5	150.0	16.5	7.5		8.0	0.9	2.0		566.0	62.4	90.3	6205000	24.6
	6000				7	17.7	574.0	63.3	28.7	15.0	11.4	80.0	8.8	45.5	5	150.0	16.5	7.5		8.0	0.9	2.0		812.0	89.5	110.0	6205000	32.2
	12000				15	8.3	1230.0	135.5	61.5	29.9	11.4	80.0	8.8	45.5	5	150.0	16.5	7.5		8.0	0.9	2.0		1468.0	161.8	157.8	6205000	51.5
	200	10000	18	19	4	155.1	140.0	15.4	7.0	2.8	26.9	80.0	8.8	45.5	3	90.0	9.9	4.5		8.0	0.9	2.0		318.0	35.0	88.7	6205000	19.9
	500				4	155.1	140.0	15.4	7.0	7.1	26.9	80.0	8.8	45.5	3	90.0	9.9	4.5		8.0	0.9	2.0		318.0	35.0	93.0	6205000	20.6
	1000				8	77.6	280.0	30.9	14.0	14.0	26.9	80.0	8.8	45.5	3	90.0	9.9	4.5		8.0	0.9	2.0		458.0	50.5	106.8	6205000	25.4
	3000				16	38.8	560.0	61.7	28.0	41.7	26.9	80.0	8.8	45.5	3	90.0	9.9	4.5		8.0	0.9	2.0		738.0	81.3	148.5	6205000	37.0
	6000				32	19.4	1120.0	123.4	56.0	83.1	26.9	80.0	8.8	45.5	3	90.0	9.9	4.5		8.0	0.9	2.0		1298.0	143.0	218.0	6205000	58.2
	12000				62	10.0	2170.0	239.1	108.5	166.2	26.9	80.0	8.8	45.5	3	90.0	9.9	4.5		8.0	0.9	2.0		2348.0	258.7	353.5	6205000	98.7
	200	30000			2	103.4	120.0	13.2	6.0	1.2	14.2	80.0	8.8	45.5	4	120.0	13.2	6.0		8.0	0.9	2.0		328.0	36.1	74.8	6205000	17.9
	500				2	103.4	120.0	13.2	6.0	3.0	14.2	80.0	8.8	45.5	4	120.0	13.2	6.0		8.0	0.9	2.0		328.0	36.1	76.6	6205000	18.2
	1000				3	68.9	180.0	19.8	9.0	5.8	14.2	80.0	8.8	45.5	4	120.0	13.2	6.0		8.0	0.9	2.0		388.0	42.8	82.5	6205000	20.2
	3000				6	34.5	360.0	39.7	18.0	17.4	14.2	80.0	8.8	45.5	4	120.0	13.2	6.0		8.0	0.9	2.0		568.0	62.6	103.1	6205000	26.7
	6000				11	18.8	660.0	72.7	33.0	34.7	14.2	80.0	8.8	45.5	4	120.0	13.2	6.0		8.0	0.9	2.0		868.0	95.7	135.4	6205000	37.2
	12000				21	9.8	1260.0	138.9	63.0	69.5	14.2	80.0	8.8	45.5	4	120.0	13.2	6.0		8.0	0.9	2.0		1468.0	161.8	200.1	6205000	58.3
	200	50000			1	124.1	85.0	9.4	4.3	0.8	11.4	80.0	8.8	45.5	5	150.0	16.5	7.5		8.0	0.9	2.0		323.0	35.6	71.4	6205000	17.2
	500				2	62.1	170.0	18.7	8.5	2.0	11.4	80.0	8.8	45.5	5	150.0	16.5	7.5		8.0	0.9	2.0		408.0	45.0	76.8	6205000	19.6
	1000				2	62.1	170.0	18.7	8.5	3.9	11.4	80.0	8.8	45.5	5	150.0	16.5	7.5		8.0	0.9	2.0		408.0	45.0	78.7	6205000	19.9
	3000				4	31.0	340.0	37.5	17.0	11.6	11.4	80.0	8.8	45.5	5	150.0	16.5	7.5		8.0	0.9	2.0		578.0	63.7	94.9	6205000	25.6
	6000				7	17.7	595.0	65.6	29.8	23.1	11.4	80.0	8.8	45.5	5	150.0	16.5	7.5		8.0	0.9	2.0		833.0	91.8	119.2	6205000	34.0
	12000				12	10.3	1020.0	112.4	51.0	46.1	11.4	80.0	8.8	45.5	5	150.0	16.5	7.5		8.0	0.9	2.0		1258.0	138.6	163.5	6205000	48.7

Table 5-3 Total cost of CO_2 marine transportation

CO2 pressure before liquefaction	DISTANCE	SHIP										Liquefaction System			CO2 tank				Loading/Unloading			TOTAL			Total amount of CO2	[Capitan,Running Cost & Harbour Fee] / year
		SHIP SIZE	SHIP SPEED		Number of Ship	Number of service	Construction	Capital Cost	Running Cost		Harbor Fee	Construction	Capital Cost	Running Cost	Number of tanks	Construction	Capital Cost	Running Cost	Construction	Capital Cost	Running Cost	Construction	Capital Cost	Running Cost & Harbour Fee		
						Running rate 85% / year			Crew, Insurance, Maintenance	Fuel																
	km	ton	(Full Load) kn	(Ballast) kn		Number/ship/ year	Million US$	Million US$	Million US$	Million US$	Million US$	Million US$	Million US$	Million US$		Million US$	Million US$	Million US$	Million US$	Million US$	Million US$	Million US$	Million US$	Million US$	ton/year	US$/tCO2
100Bar	200	10000	15	16	4	155.1	136.0	15.0	6.8	1.8	26.9	30.0	3.3	6.0	3	90.0	9.9	4.5	8.0	0.9	2.0	264.0	29.1	48.0	6205000	12.4
	500				6	103.4	204.0	22.5	10.2	4.3	26.9	30.0	3.3	6.0	3	90.0	9.9	4.5	8.0	0.9	2.0	332.0	36.6	53.9	6205000	14.6
	1000				8	77.6	272.0	30.0	13.6	8.6	26.9	30.0	3.3	6.0	3	90.0	9.9	4.5	8.0	0.9	2.0	400.0	44.1	61.6	6205000	17.0
	3000				20	31.0	680.0	74.9	34.0	25.9	26.9	30.0	3.3	6.0	3	90.0	9.9	4.5	8.0	0.9	2.0	808.0	89.0	99.3	6205000	30.3
	6000				38	16.3	1292.0	142.4	64.6	51.7	26.9	30.0	3.3	6.0	3	90.0	9.9	4.5	8.0	0.9	2.0	1420.0	156.5	155.6	6205000	50.3
	12000				74	8.4	2516.0	277.3	125.8	103.2	26.9	30.0	3.3	6.0	3	90.0	9.9	4.5	8.0	0.9	2.0	2644.0	291.4	268.4	6205000	90.2
	200	30000			2	103.4	116.0	12.8	5.8	0.8	14.2	30.0	3.3	6.0	4	120.0	13.2	6.0	8.0	0.9	2.0	274.0	30.2	34.7	6205000	10.5
	500				2	103.4	116.0	12.8	5.8	1.8	14.2	30.0	3.3	6.0	4	120.0	13.2	6.0	8.0	0.9	2.0	274.0	30.2	35.8	6205000	10.6
	1000				3	68.9	174.0	19.2	8.7	3.7	14.2	30.0	3.3	6.0	4	120.0	13.2	6.0	8.0	0.9	2.0	332.0	36.6	40.5	6205000	12.4
	3000				7	29.5	406.0	44.7	20.3	11.0	14.2	30.0	3.3	6.0	4	120.0	13.2	6.0	8.0	0.9	2.0	564.0	62.2	59.4	6205000	19.6
	6000				13	15.9	754.0	83.1	37.7	22.0	14.2	30.0	3.3	6.0	4	120.0	13.2	6.0	8.0	0.9	2.0	912.0	100.5	87.8	6205000	30.3
	12000				24	8.6	1392.0	153.4	69.6	43.8	14.2	30.0	3.3	6.0	4	120.0	13.2	6.0	8.0	0.9	2.0	1550.0	170.8	141.6	6205000	50.3
	200	50000			1	124.1	82.0	9.0	4.1	0.5	11.4	30.0	3.3	6.0	5	150.0	16.5	7.5	8.0	0.9	2.0	270.0	29.8	31.5	6205000	9.9
	500				2	62.1	164.0	18.1	8.2	1.3	11.4	30.0	3.3	6.0	5	150.0	16.5	7.5	8.0	0.9	2.0	352.0	38.8	36.3	6205000	12.1
	1000				2	62.1	164.0	18.1	8.2	2.5	11.4	30.0	3.3	6.0	5	150.0	16.5	7.5	8.0	0.9	2.0	352.0	38.8	37.6	6205000	12.3
	3000				4	31.0	328.0	36.1	16.4	7.5	11.4	30.0	3.3	6.0	5	150.0	16.5	7.5	8.0	0.9	2.0	516.0	56.9	50.8	6205000	17.3
	6000				7	17.7	574.0	63.3	28.7	15.0	11.4	30.0	3.3	6.0	5	150.0	16.5	7.5	8.0	0.9	2.0	762.0	84.0	70.5	6205000	24.9
	12000				15	8.3	1230.0	135.5	61.5	29.9	11.4	30.0	3.3	6.0	5	150.0	16.5	7.5	8.0	0.9	2.0	1418.0	156.3	118.3	6205000	44.2
	200	10000	18	19	4	155.1	140.0	15.4	7.0	2.8	26.9	30.0	3.3	6.0	3	90.0	9.9	4.5	8.0	0.9	2.0	268.0	29.5	49.2	6205000	12.7
	500				4	155.1	140.0	15.4	7.0	7.1	26.9	30.0	3.3	6.0	3	90.0	9.9	4.5	8.0	0.9	2.0	268.0	29.5	53.5	6205000	13.4
	1000				8	77.6	280.0	30.9	14.0	14.0	26.9	30.0	3.3	6.0	3	90.0	9.9	4.5	8.0	0.9	2.0	408.0	45.0	67.3	6205000	18.1
	3000				16	38.8	560.0	61.7	28.0	41.7	26.9	30.0	3.3	6.0	3	90.0	9.9	4.5	8.0	0.9	2.0	688.0	75.8	109.0	6205000	29.8
	6000				32	19.4	1120.0	123.4	56.0	83.1	26.9	30.0	3.3	6.0	3	90.0	9.9	4.5	8.0	0.9	2.0	1248.0	137.5	178.5	6205000	50.9
	12000				62	10.0	2170.0	239.1	108.5	166.2	26.9	30.0	3.3	6.0	3	90.0	9.9	4.5	8.0	0.9	2.0	2298.0	253.2	314.0	6205000	91.4
	200	30000			2	103.4	120.0	13.2	6.0	1.2	14.2	30.0	3.3	6.0	4	120.0	13.2	6.0	8.0	0.9	2.0	278.0	30.6	35.3	6205000	10.6
	500				2	103.4	120.0	13.2	6.0	3.0	14.2	30.0	3.3	6.0	4	120.0	13.2	6.0	8.0	0.9	2.0	278.0	30.6	37.1	6205000	10.9
	1000				3	68.9	180.0	19.8	9.0	5.8	14.2	30.0	3.3	6.0	4	120.0	13.2	6.0	8.0	0.9	2.0	338.0	37.2	43.0	6205000	12.9
	3000				6	34.5	360.0	39.7	18.0	17.4	14.2	30.0	3.3	6.0	4	120.0	13.2	6.0	8.0	0.9	2.0	518.0	57.1	63.6	6205000	19.4
	6000				11	18.8	660.0	72.7	33.0	34.7	14.2	30.0	3.3	6.0	4	120.0	13.2	6.0	8.0	0.9	2.0	818.0	90.1	95.9	6205000	30.0
	12000				21	9.8	1260.0	138.9	63.0	69.5	14.2	30.0	3.3	6.0	4	120.0	13.2	6.0	8.0	0.9	2.0	1418.0	156.3	160.6	6205000	51.1
	200	50000			1	124.1	85.0	9.4	4.3	0.8	11.4	30.0	3.3	6.0	5	150.0	16.5	7.5	8.0	0.9	2.0	273.0	30.1	31.9	6205000	10.0
	500				2	62.1	170.0	18.7	8.5	2.0	11.4	30.0	3.3	6.0	5	150.0	16.5	7.5	8.0	0.9	2.0	358.0	39.5	37.3	6205000	12.4
	1000				2	62.1	170.0	18.7	8.5	3.9	11.4	30.0	3.3	6.0	5	150.0	16.5	7.5	8.0	0.9	2.0	358.0	39.5	39.2	6205000	12.7
	3000				4	31.0	340.0	37.5	17.0	11.6	11.4	30.0	3.3	6.0	5	150.0	16.5	7.5	8.0	0.9	2.0	528.0	58.2	55.4	6205000	18.3
	6000				7	17.7	595.0	65.6	29.8	23.1	11.4	30.0	3.3	6.0	5	150.0	16.5	7.5	8.0	0.9	2.0	783.0	86.3	79.7	6205000	26.7
	12000				12	10.3	1020.0	112.4	51.0	46.1	11.4	30.0	3.3	6.0	5	150.0	16.5	7.5	8.0	0.9	2.0	1208.0	133.1	124.0	6205000	41.4

Table 5-4 CO_2 emission from CO_2 marine transportation (atmospheric pressure CO_2 supply)

DISTANCE	SHIP SIZE	SHIP SPEED		Liquefaction System		CO2tank	SHIP			TOTAL
				Power	dehydration	Boil-off	Fuel	Boil-off (going)	Boil-off (returning)	
km	ton	(Full Load) kn	(Ballast) kn	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year
200	10000	15	16	636013	7362	37230	32514	4137	3620	720875
500				636013	7362	37230	75866	9308	8790	774569
1000				636013	7362	37230	151733	18615	17581	868534
3000				636013	7362	37230	455199	55845	52743	1244391
6000				636013	7362	37230	908230	111690	104968	1805493
12000				636013	7362	37230	1814292	223380	209419	2927696
200	30000			636013	7362	49640	13816	4137	3620	714588
500				636013	7362	49640	32238	9308	8790	743351
1000				636013	7362	49640	64477	18615	17581	793688
3000				636013	7362	49640	193431	55845	52743	995033
6000				636013	7362	49640	385940	111690	104968	1295613
12000				636013	7362	49640	770959	223380	209419	1896772
200	50000			636013	7362	62050	9432	4137	3620	722613
500				636013	7362	62050	22007	9308	8790	745530
1000				636013	7362	62050	44014	18615	17581	785635
3000				636013	7362	62050	132042	55845	52743	946055
6000				636013	7362	62050	263456	111690	104968	1185539
12000				636013	7362	62050	526283	223380	209419	1664507
200	10000	18	19	636013	7362	37230	49938	3103	3103	736748
500				636013	7362	37230	124845	7756	7756	820962
1000				636013	7362	37230	245528	15513	14995	956641
3000				636013	7362	37230	732422	46538	44469	1504033
6000				636013	7362	37230	1460682	93075	88421	2322783
12000				636013	7362	37230	2921364	186150	176843	3964961
200	30000			636013	7362	49640	20882	3103	3103	720102
500				636013	7362	49640	52205	7756	7756	760732
1000				636013	7362	49640	102669	15513	14995	826192
3000				636013	7362	49640	306268	46538	44469	1090289
6000				636013	7362	49640	610795	93075	88421	1485307
12000				636013	7362	49640	1221591	186150	176843	2277598
200	50000			636013	7362	62050	13859	3103	3103	725489
500				636013	7362	62050	34649	7756	7756	755586
1000				636013	7362	62050	68142	15513	14995	804075
3000				636013	7362	62050	203272	46538	44469	999704
6000				636013	7362	62050	405390	93075	88421	1292311
12000				636013	7362	62050	810780	186150	176843	1879197

Table 5-5 CO_2 emission from CO_2 marine transportation (pre-pressurized CO_2 supply)

DISTANCE	SHIP SIZE	SHIP SPEED		Liquefaction System	CO2tank	SHIP			TOTAL
				Power	Boil-off	Fuel	Boil-off (going)	Boil-off (returning)	
km	ton	(Full Load) kn	(Ballast) kn	ton/year	ton/year	ton/year	ton/year	ton/year	ton/year
200	10000	15	16	74460	37230	32514	4137	3620	151960
500				74460	37230	75866	9308	8790	205654
1000				74460	37230	151733	18615	17581	299619
3000				74460	37230	455199	55845	52743	675476
6000				74460	37230	908230	111690	104968	1236578
12000				74460	37230	1814292	223380	209419	2358781
200	30000			74460	49640	13816	4137	3620	145673
500				74460	49640	32238	9308	8790	174436
1000				74460	49640	64477	18615	17581	224773
3000				74460	49640	193431	55845	52743	426118
6000				74460	49640	385940	111690	104968	726698
12000				74460	49640	770959	223380	209419	1327858
200	50000			74460	62050	9432	4137	3620	153698
500				74460	62050	22007	9308	8790	176615
1000				74460	62050	44014	18615	17581	216720
3000				74460	62050	132042	55845	52743	377140
6000				74460	62050	263456	111690	104968	616624
12000				74460	62050	526283	223380	209419	1095592
200	10000	18	19	74460	37230	49938	3103	3103	167833
500				74460	37230	124845	7756	7756	252047
1000				74460	37230	245528	15513	14995	387726
3000				74460	37230	732422	46538	44469	935118
6000				74460	37230	1460682	93075	88421	1753868
12000				74460	37230	2921364	186150	176843	3396046
200	30000			74460	49640	20882	3103	3103	151187
500				74460	49640	52205	7756	7756	191817
1000				74460	49640	102669	15513	14995	257277
3000				74460	49640	306268	46538	44469	521374
6000				74460	49640	610795	93075	88421	916392
12000				74460	49640	1221591	186150	176843	1708683
200	50000			74460	62050	13859	3103	3103	156574
500				74460	62050	34649	7756	7756	186671
1000				74460	62050	68142	15513	14995	235160
3000				74460	62050	203272	46538	44469	430789
6000				74460	62050	405390	93075	88421	723396
12000				74460	62050	810780	186150	176843	1310283

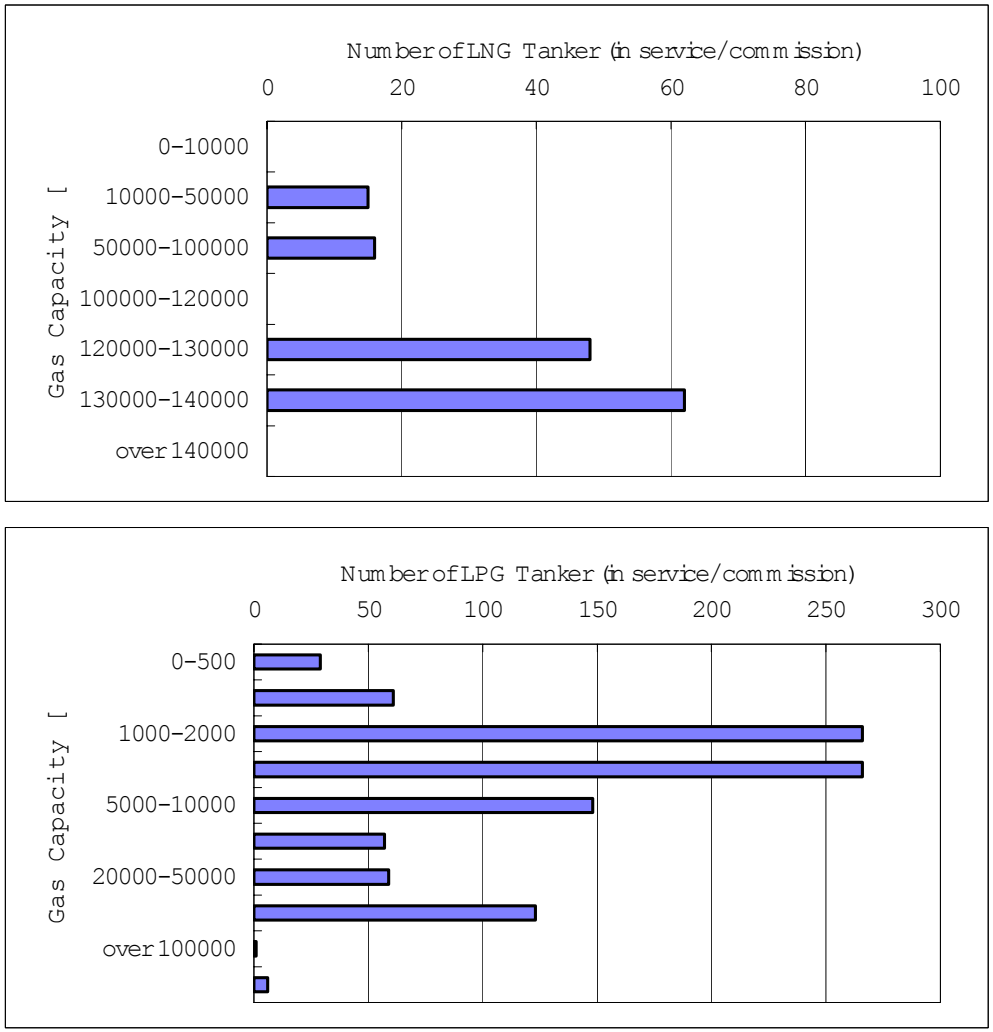


Fig.2-1 Number and capacity of gas transportation ships in service or commission

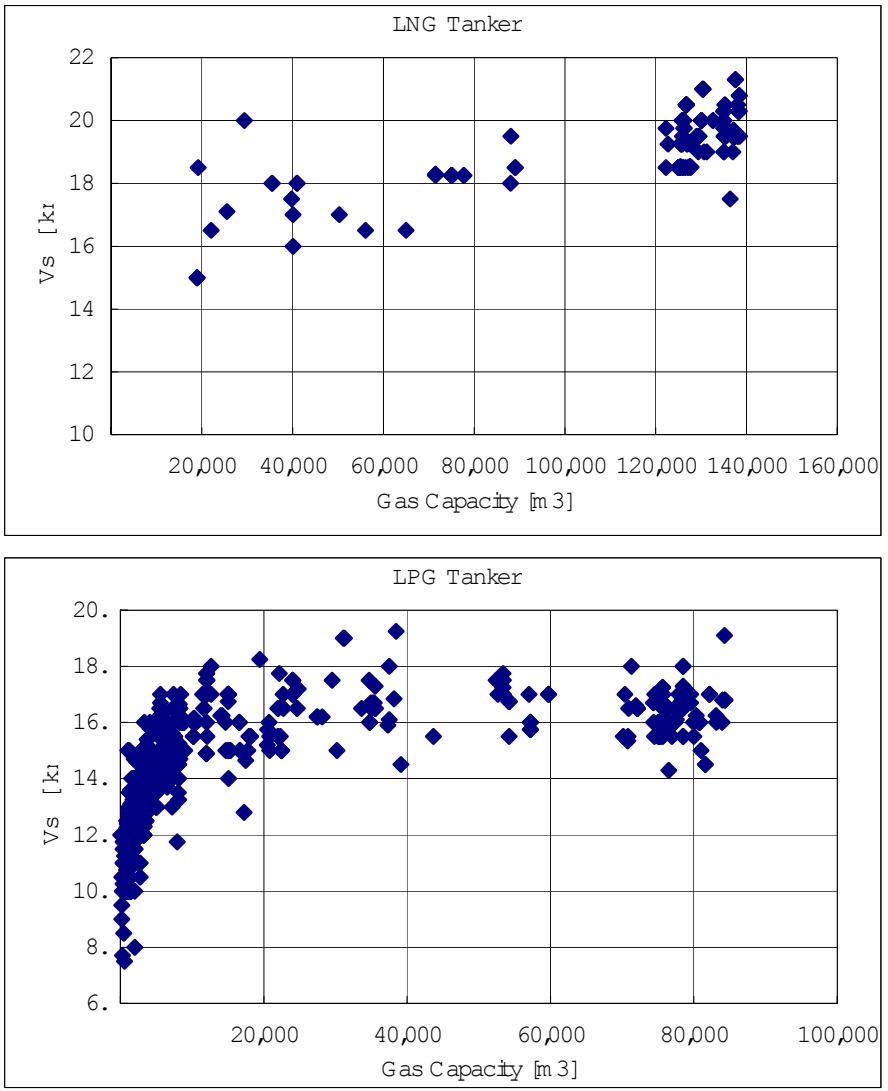


Fig.2-2 Speed of gas transportation ship

Fig.2-3　LNG carrier of 135,000m^3 capacity " AL JASRA"

Fig.2-4　LPG carrier of 78,000m^3 capacity　"GAS DIANA"

Fig.2-5 Semi Pressurized LPG carrier of 30,207m^3 capacity "DONAU "

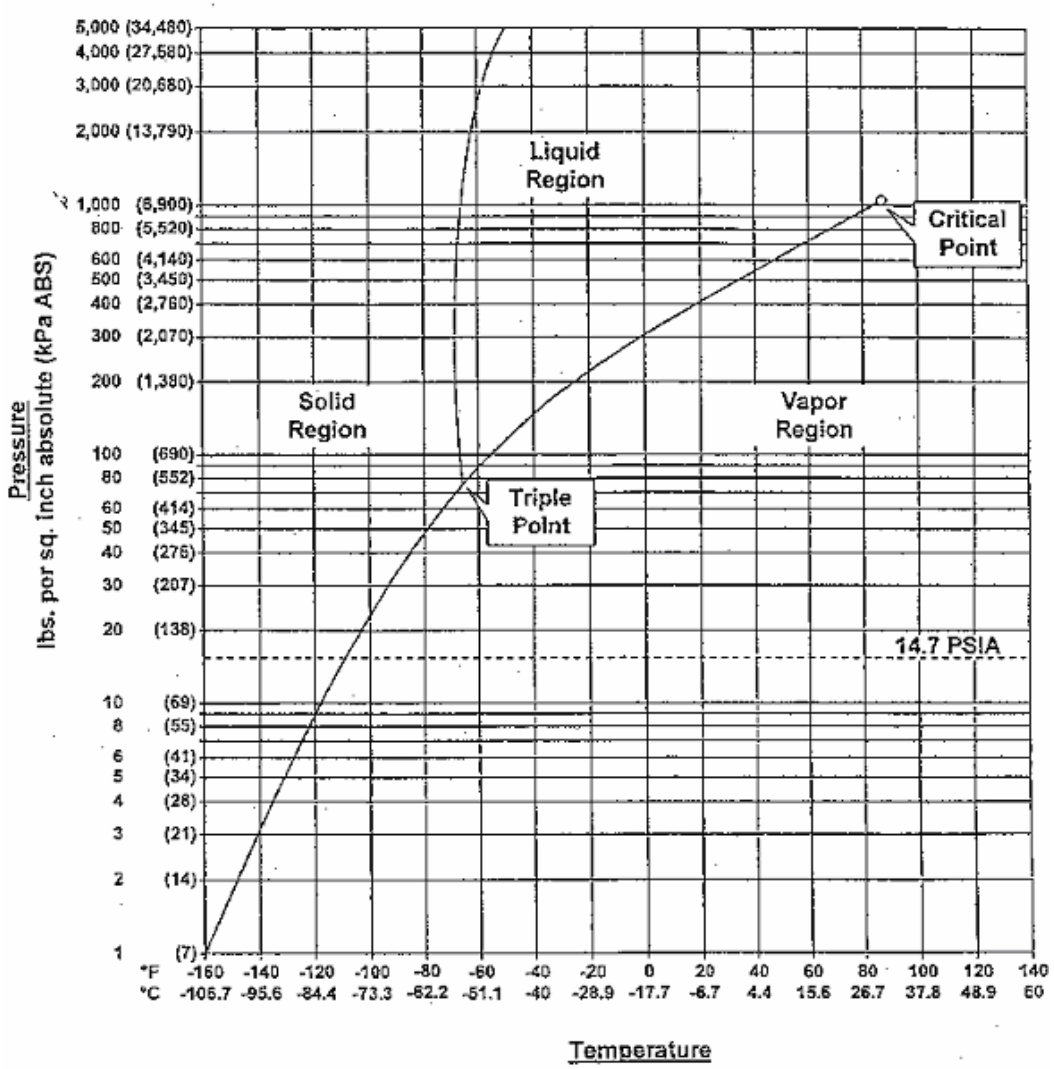


Fig.2-6 Phase diagram of CO_2

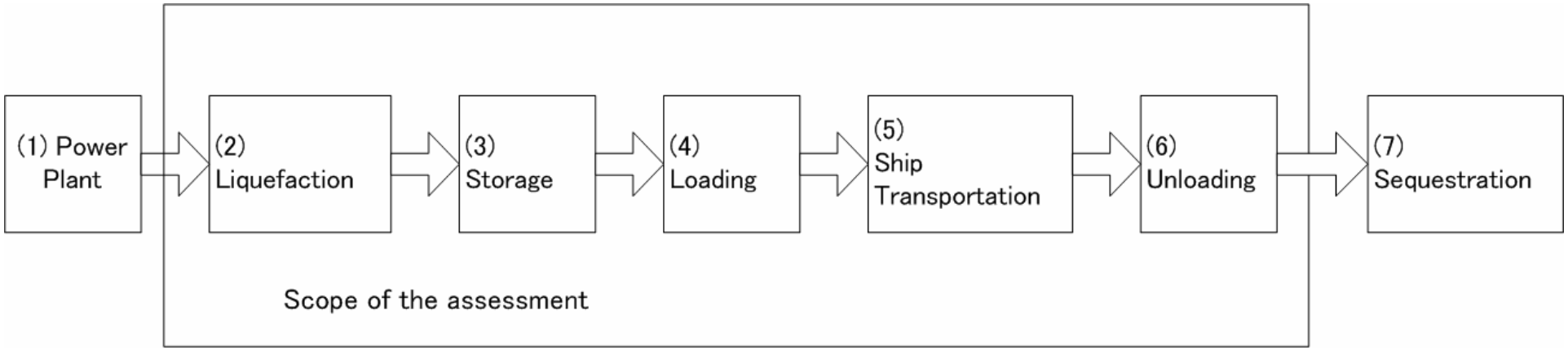
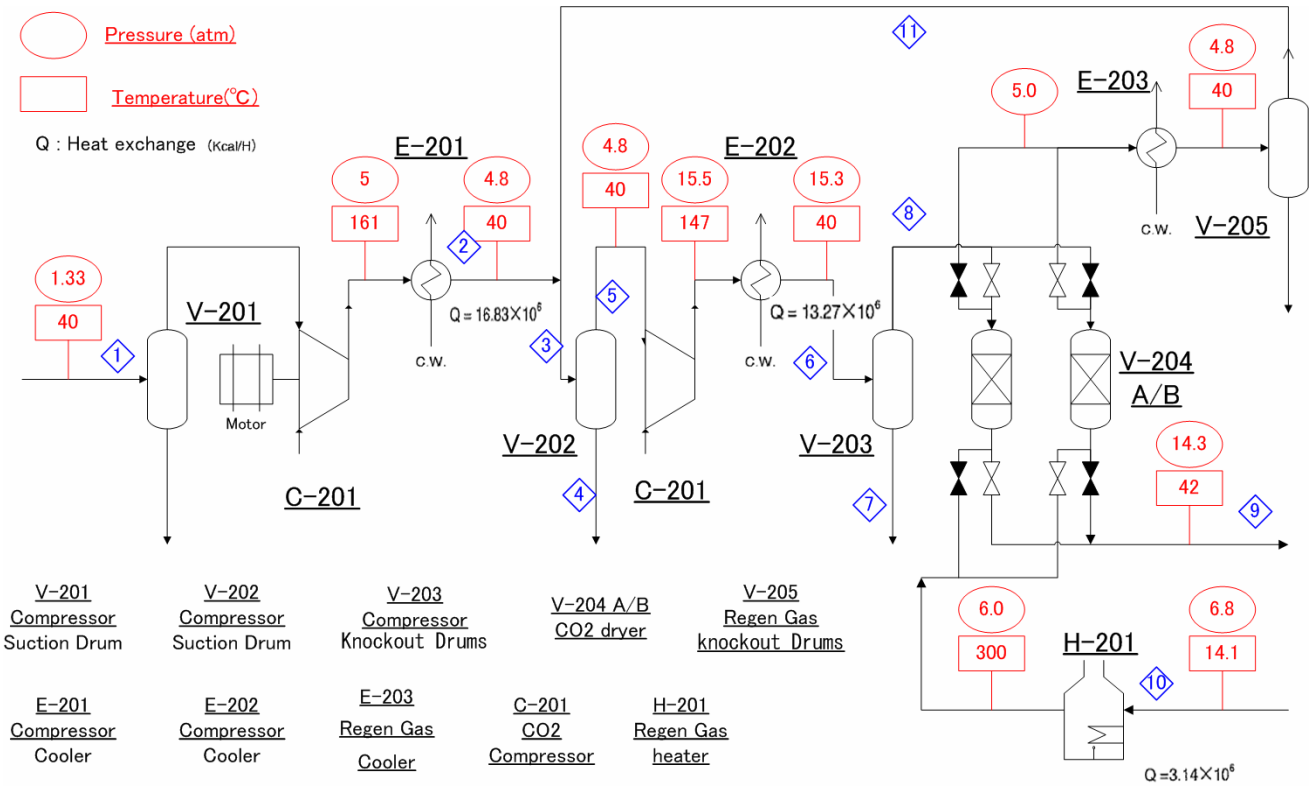
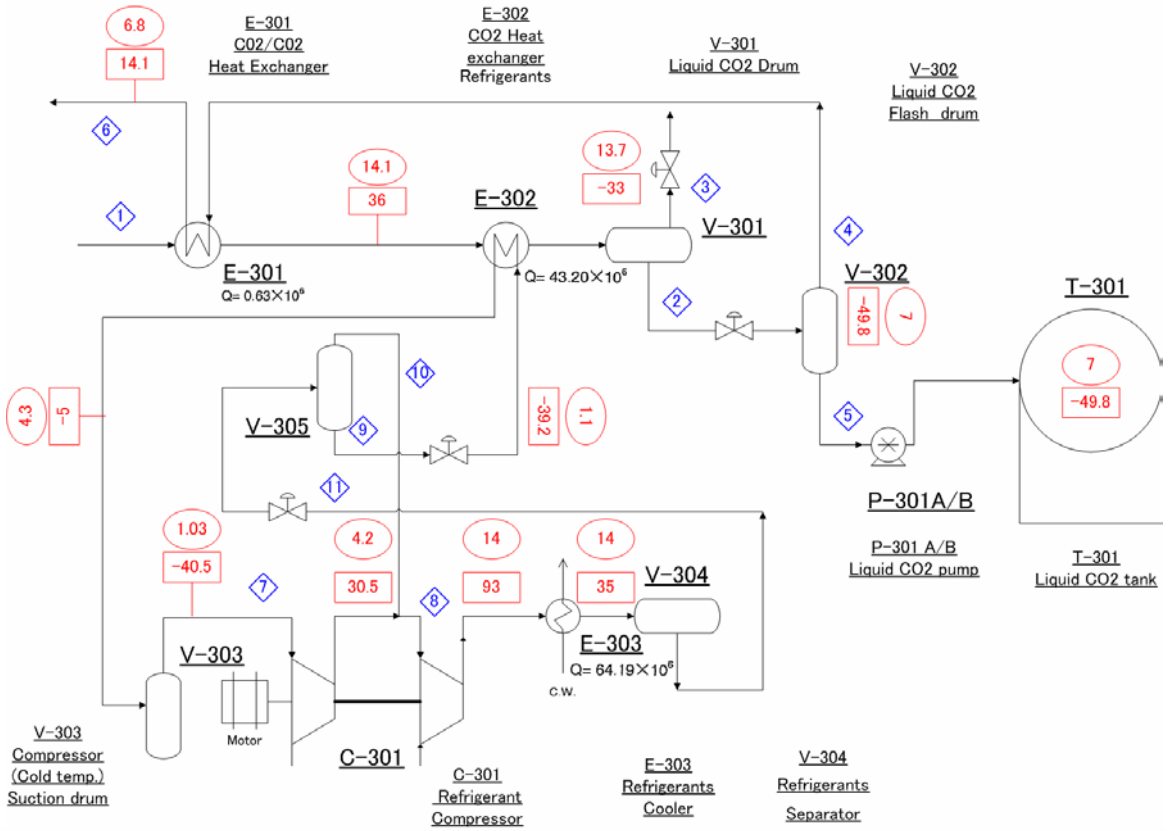


Fig.3-1 CO_2 marine transportation system



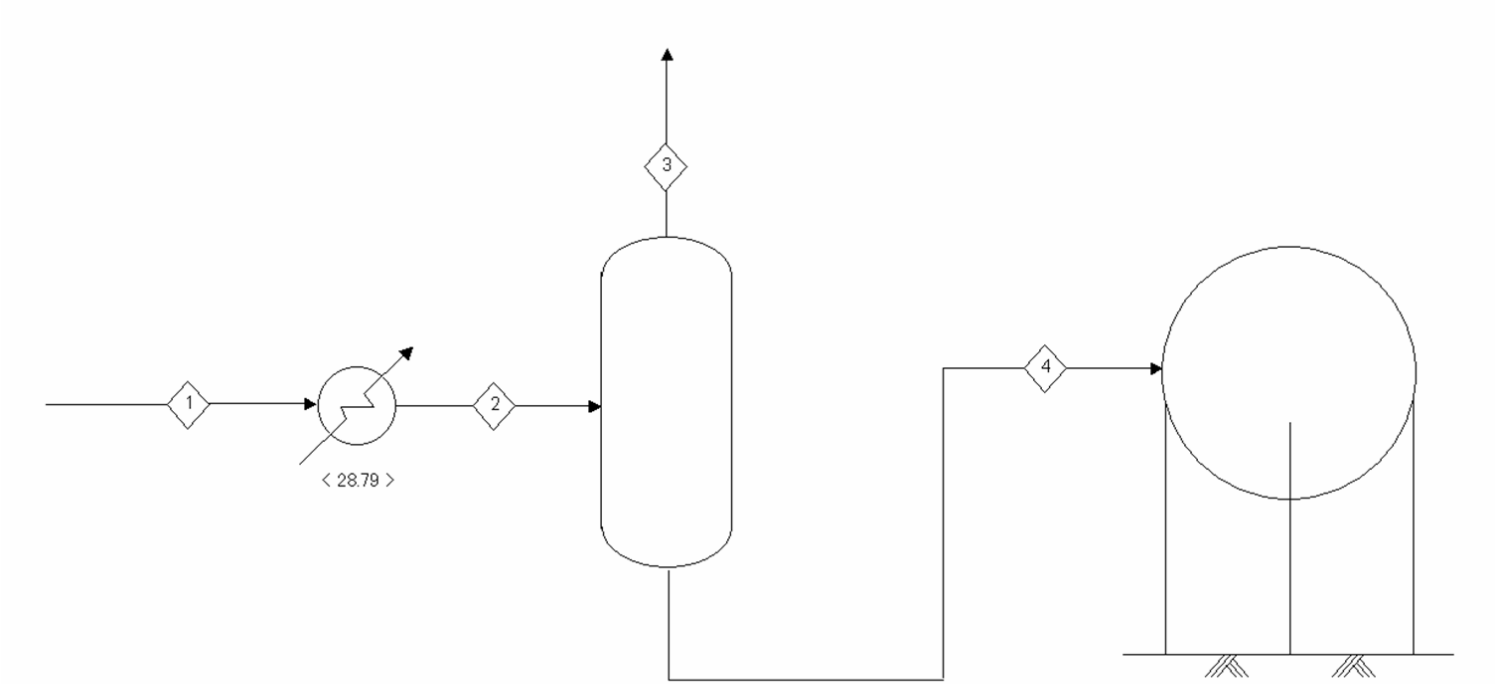
STREAM No.	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪
COMPONENT (Mol %)											
CO_2	94.26	94.29	94.59	0	98.26	98.26	0	99.33	99.82	99.05	93.48
H_2O	5.65	5.62	5.24	100	1.56	1.56	100	0.49	0	0	5.62
N_2	0.09	0.09	0.17	0	0.18	0.18	0	0.18	0.18	0.95	0.90
R22											
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Mol. Wt.	42.53	42.53	42.62	18.02	43.58	43.58	18.02	43.86	43.98	43.86	42.80
TEMPERATURE (℃)	40	40	40	40	40	40	40	40	42	14.1	40
PRESSURE (ata)	1.33	4.8	4.8	4.8	4.8	15.3	15.3	15.3	14.3	6.8	4.8
FLOW RATE (kg·mol/H)	17,967	17,962	19,829	742	19,087	19,087	205	18,882	18,790	1,838	1,867
FLOW RATE (Ton/H)	764.1	763.9	845.1	13.4	831.8	831.8	3.7	828.2	826.4	80.6	79.9

Fig.4-1 a) CO_2 liquefaction system ; CO_2 gas of atmospheric pressure supply(to be continued)



STREAM No.	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩	⑪
COMPONENT (Mol %) CO_2	99.82	99.9	95.94	99.05	99.99	99.05					
H_2O	0	0	0	0	0	0					
N_2	0.18	0.1	4.06	0.95	0.01	0.95					
R22							100.00	100.00	100.00	100.00	100.00
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	10000	100.00	100.00
Mol. Wt.	43.98	43.99	43.36	43.86	44.01	43.86	86.47	86.47	86.47	86.47	86.47
TEMPERATURE (℃)	42	-33	-33	-49.8	-49.8	14.1	-40.5	22.0	-5.0	-5.0	35
PRESSURE (ata)	14.3	13.7	13.7	7	7	6.8	1.03	4.2	4.3	4.3	14
FLOW RATE (kg·mol/H)	18,790	18,436	353	1,838	16,598	1,838	18,126	23,933	18,126	5,808	23,933
FLOW RATE (Ton/H)	826.4	811.0	15.3	80.6	730.5	80.6	1,567.3	2,069.5	1,567.3	502.2	2,069.5

Fig.4-1 b) CO_2 liquefaction system ; CO_2 gas of atmospheric pressure supply(continued)



STREAM NO.		1	2	3	4
TEMPERATURE	℃	20	-45	-46	-46
PRESSURE	kg/cm²G	103.30	102.80	7.23	7.23
COMPONENT					
N_2	mol%-Wet	0.1	0.1	3.7	0.0
CO_2		99.9	99.9	96.3	100.0
Total		100.0	100.0	100.0	100.0
FLOW RATE	m^3N/h-Wet	424,835	424,835	5,683	419,152

Fig.4-2 CO_2 liquefaction system ; pre-pressurized

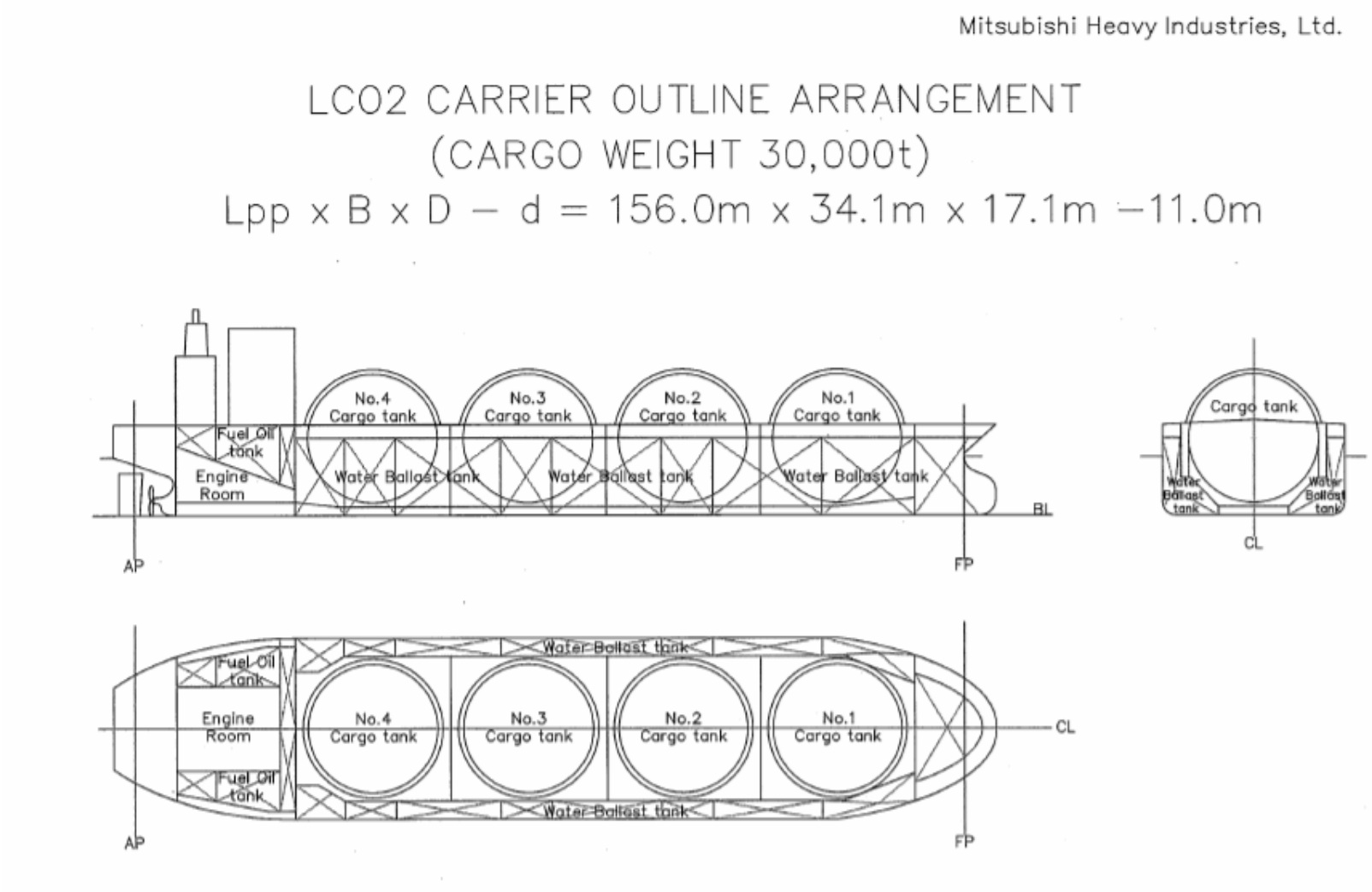


Fig.4-3 Conceptual design of typical CO_2 carrier

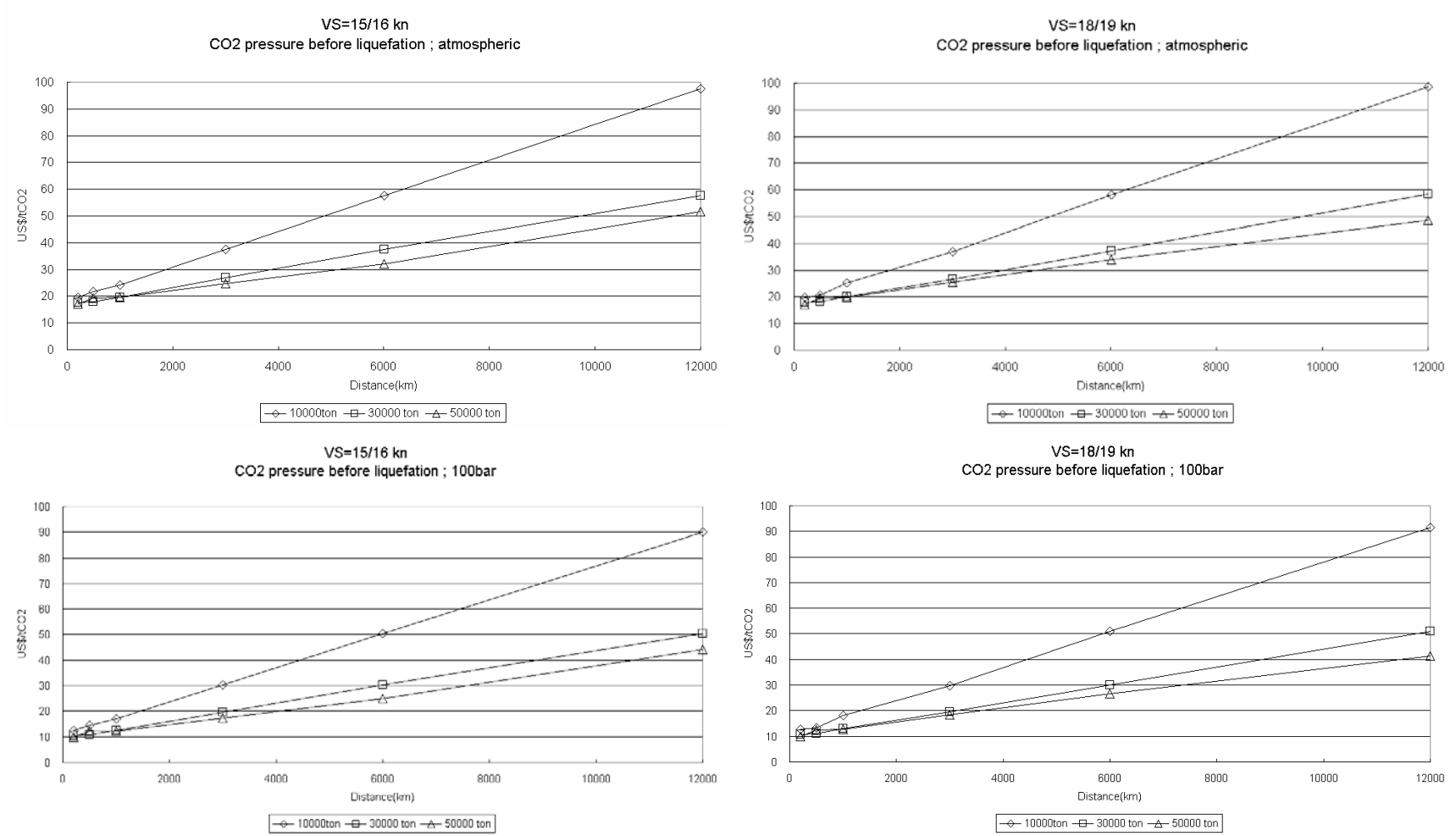


Fig.5-1 Total cost (Capital and running)

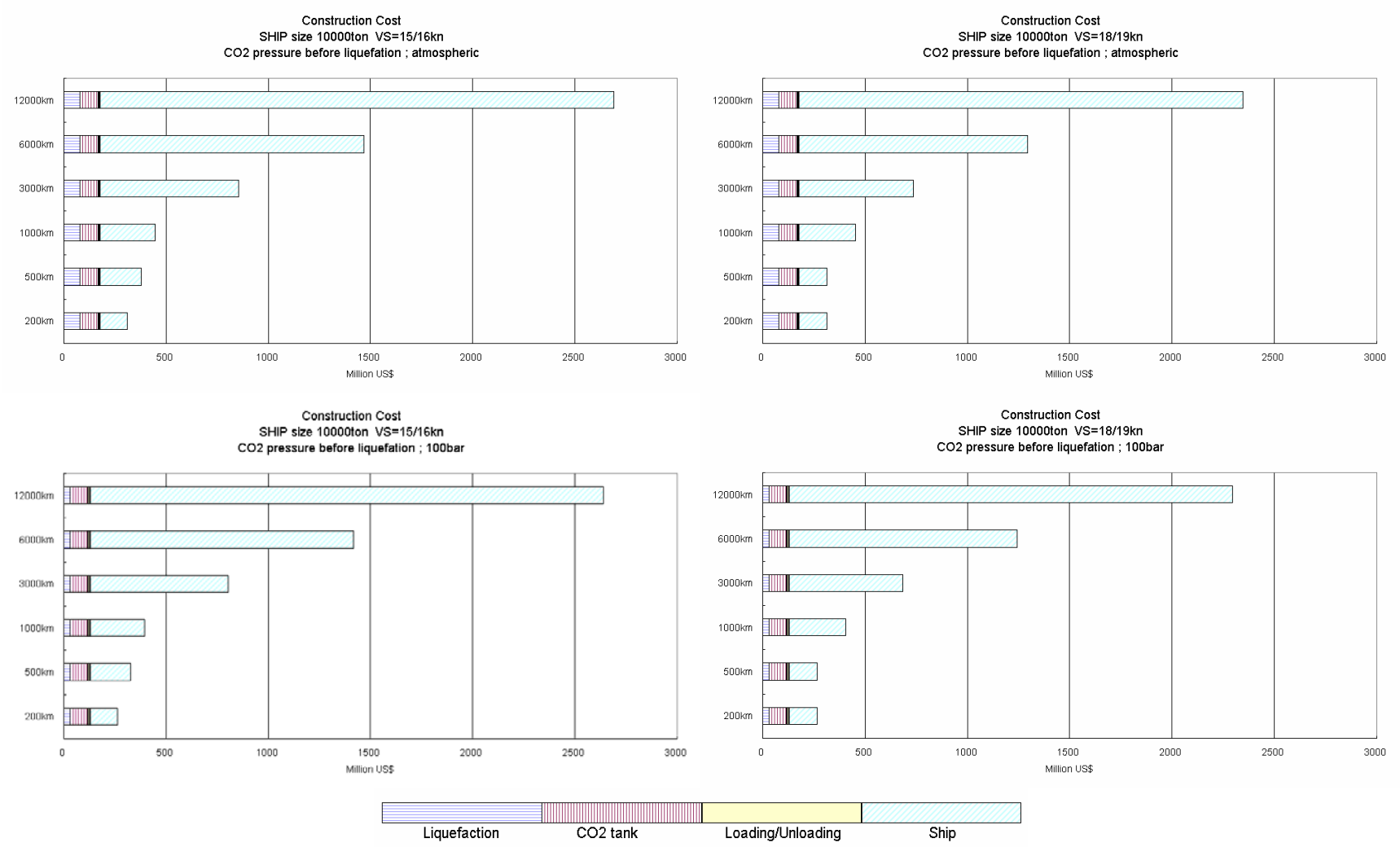


Fig.5-2 Construction cost (Ship size =10,000 tonne)

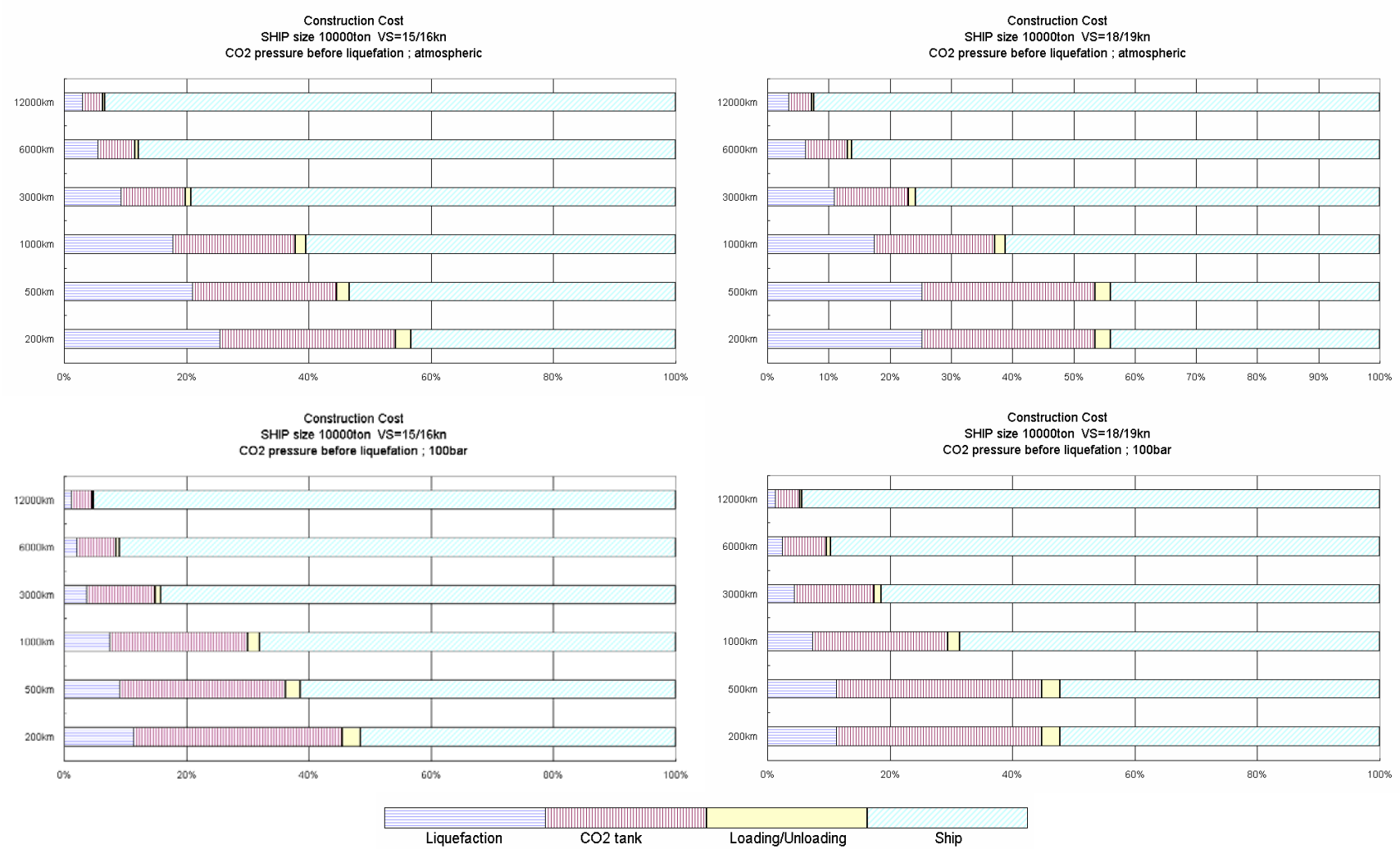


Fig.5-3 Share of construction cost (Ship size =10,000 tonne)

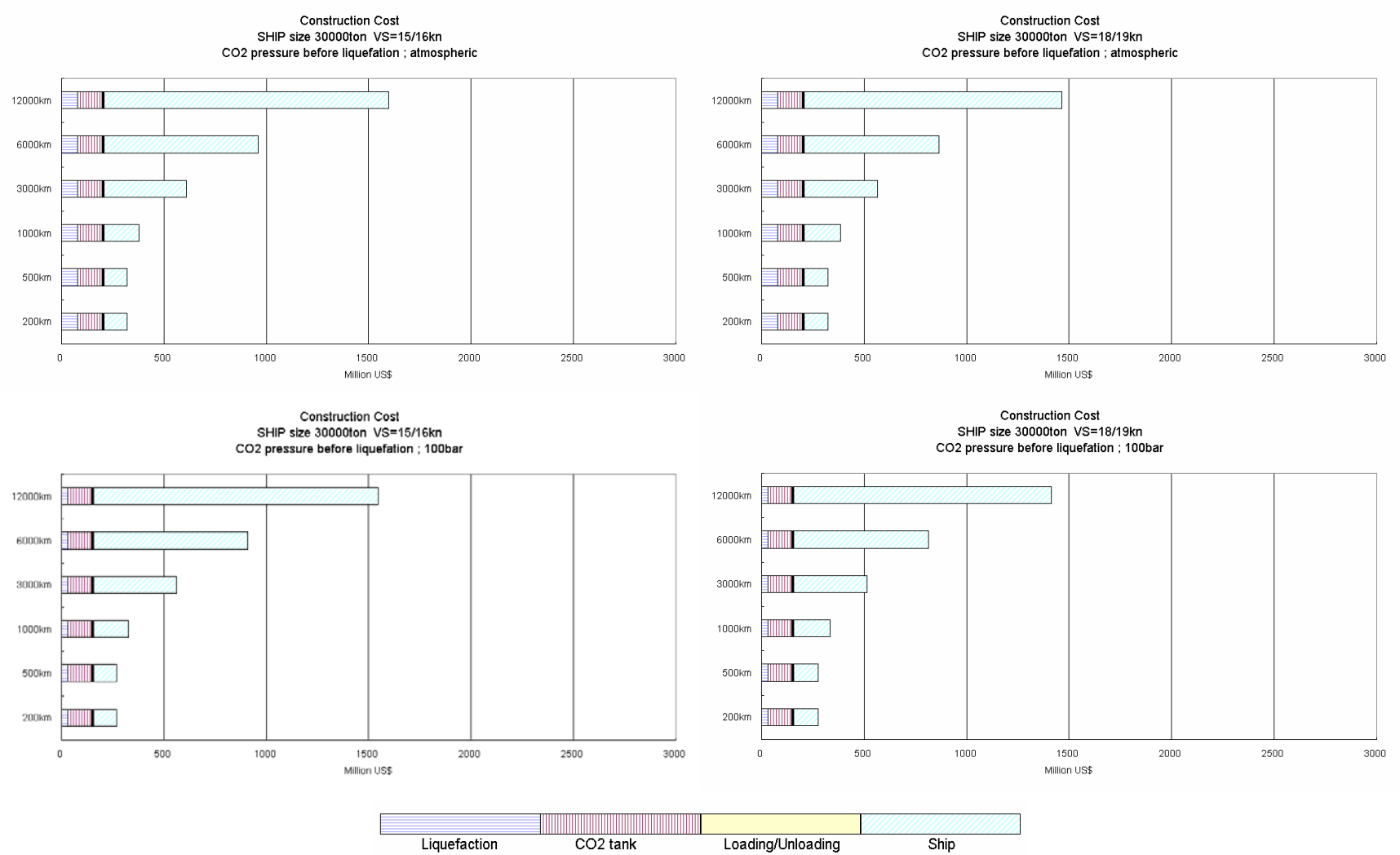


Fig.5-4 Construction cost (Ship size =30,000 tonne)

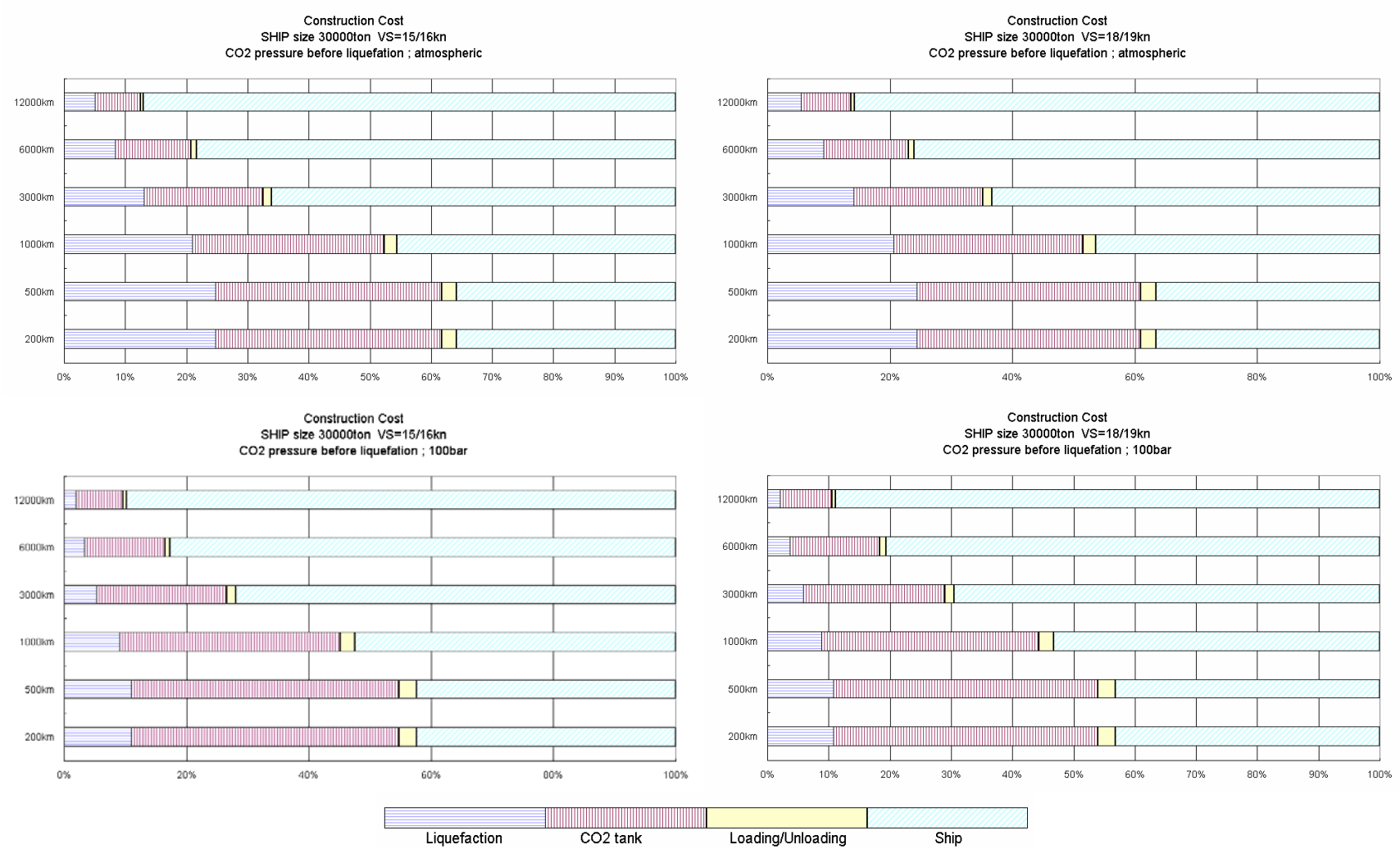


Fig.5-5 Share of construction cost (Ship size =30,000 tonne)

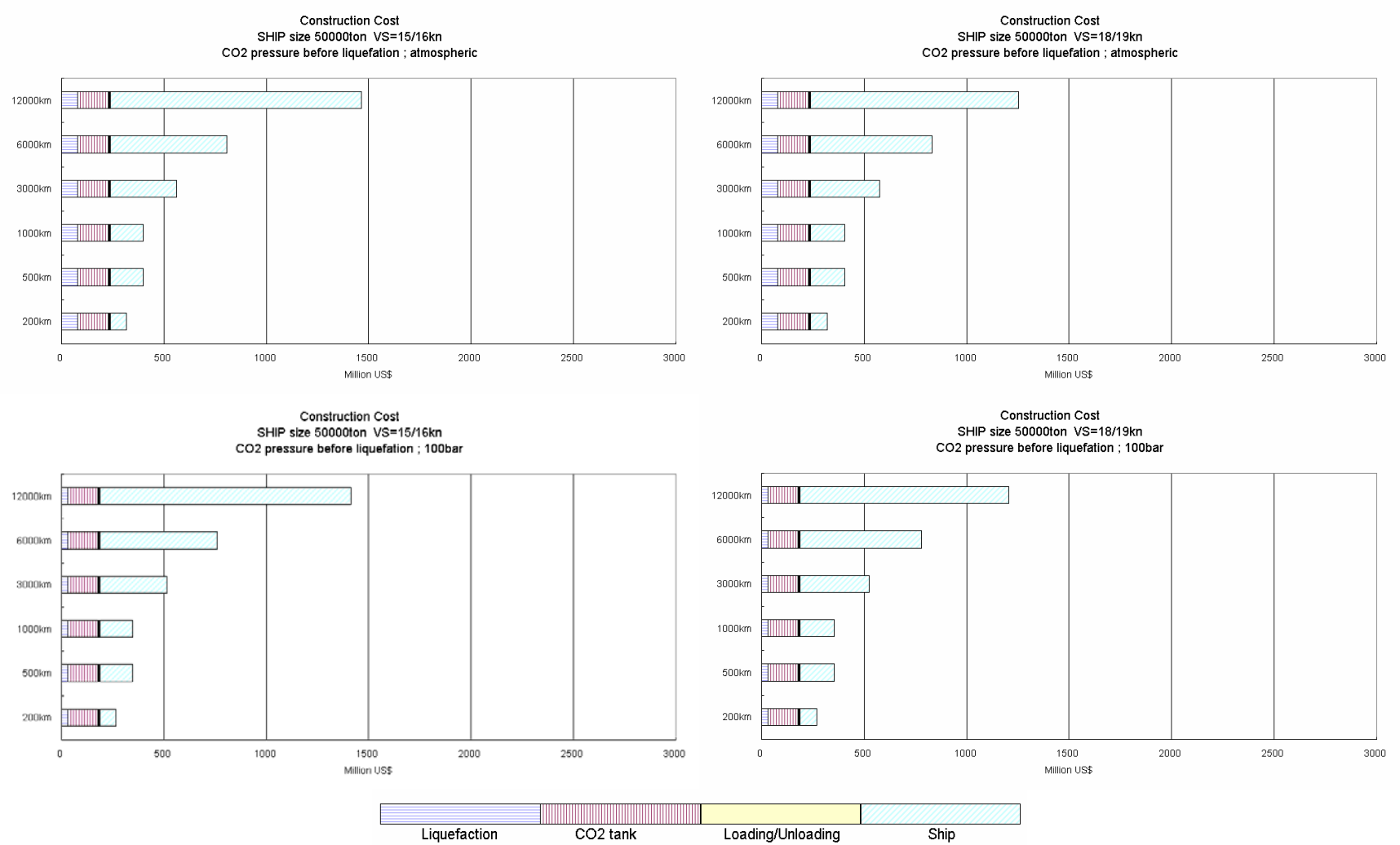


Fig.5-6 Construction cost (Ship size =50,000 tonne)

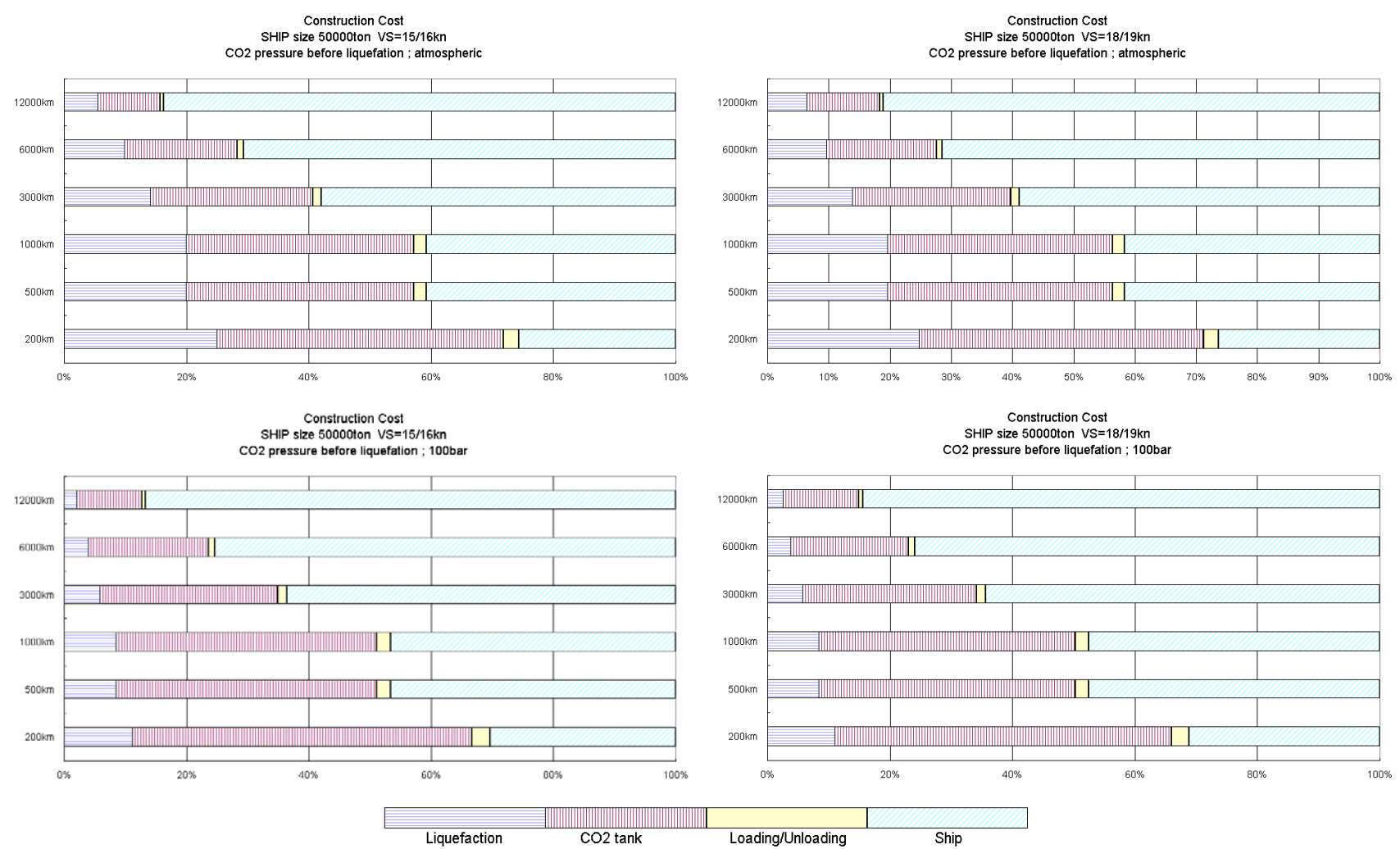


Fig.5-7 Share of construction cost (Ship size =50,000 tonne)

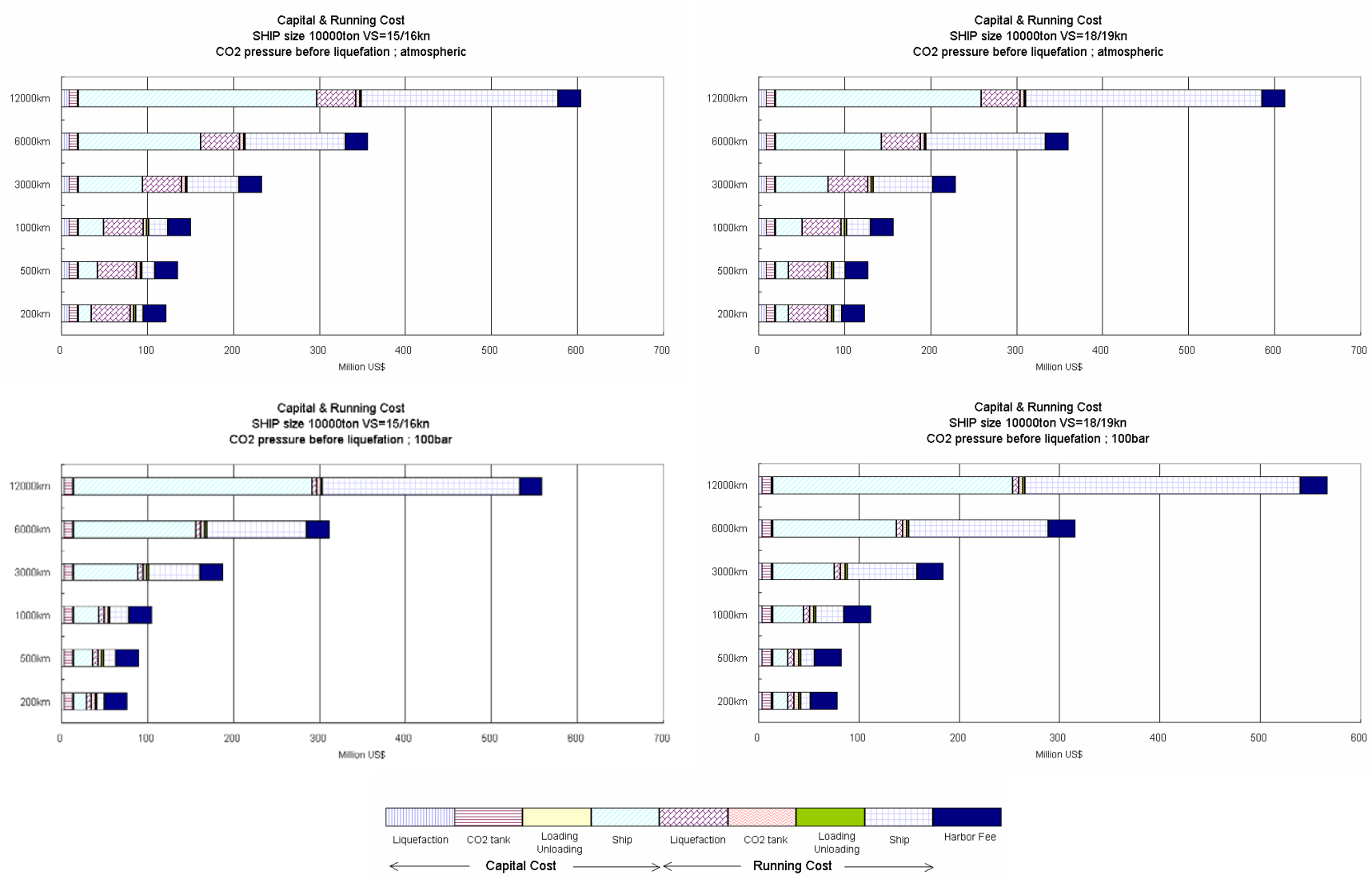


Fig.5-8 Capital and running cost (Ship size =10,000 tonne)

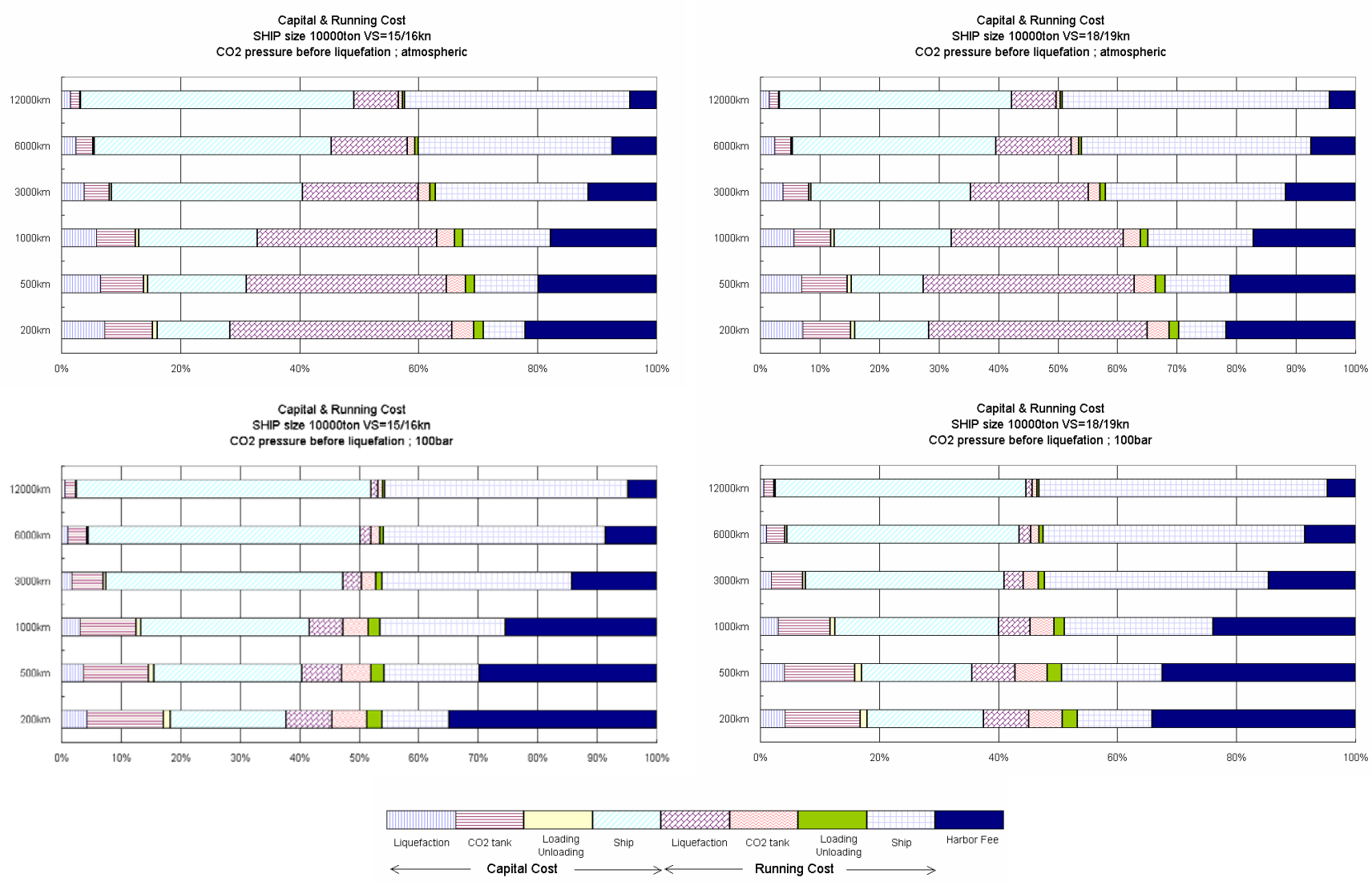


Fig.5-9 Share of capital and running cost (Ship size =10,000 tonne)

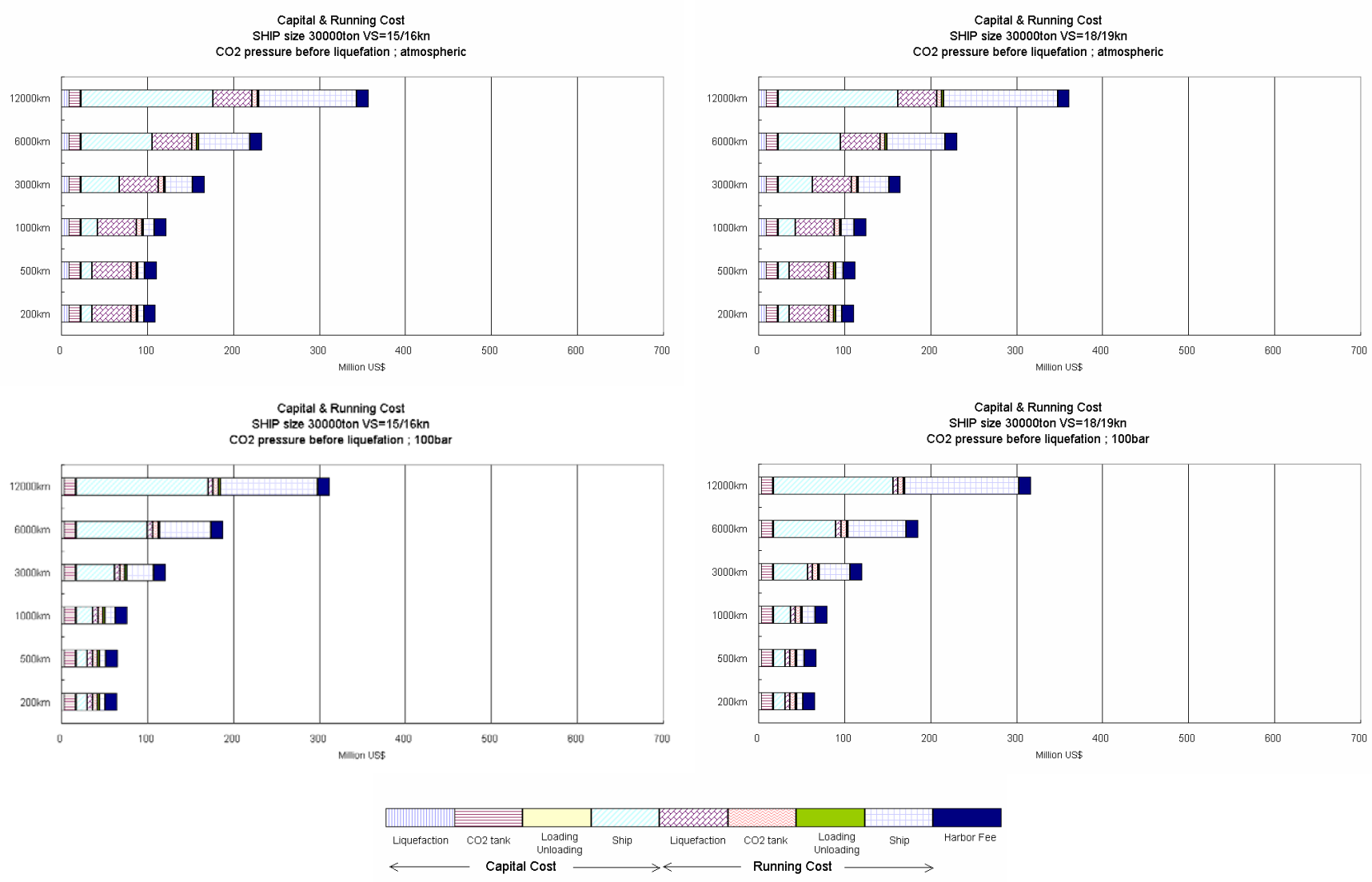


Fig.5-10 Capital and running cost (Ship size =30,000 tonne)

Fig.5-11 Share of capital and running cost (Ship size =30,000 tonne)

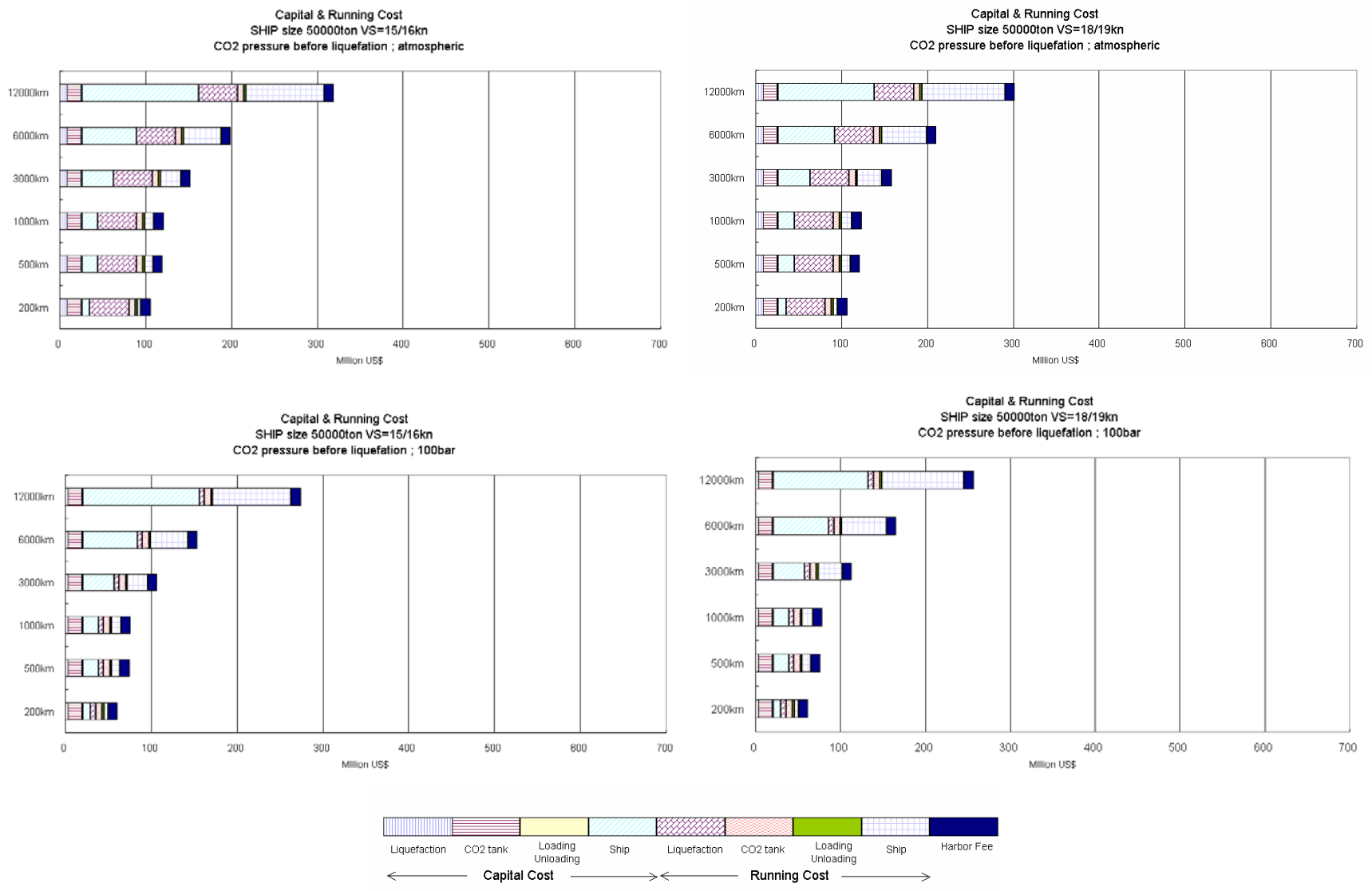


Fig.5-12 Capital and running cost (Ship size =50,000 tonne)

Fig.5-13 Share of capital and running cost (Ship size =50,000 tonne)

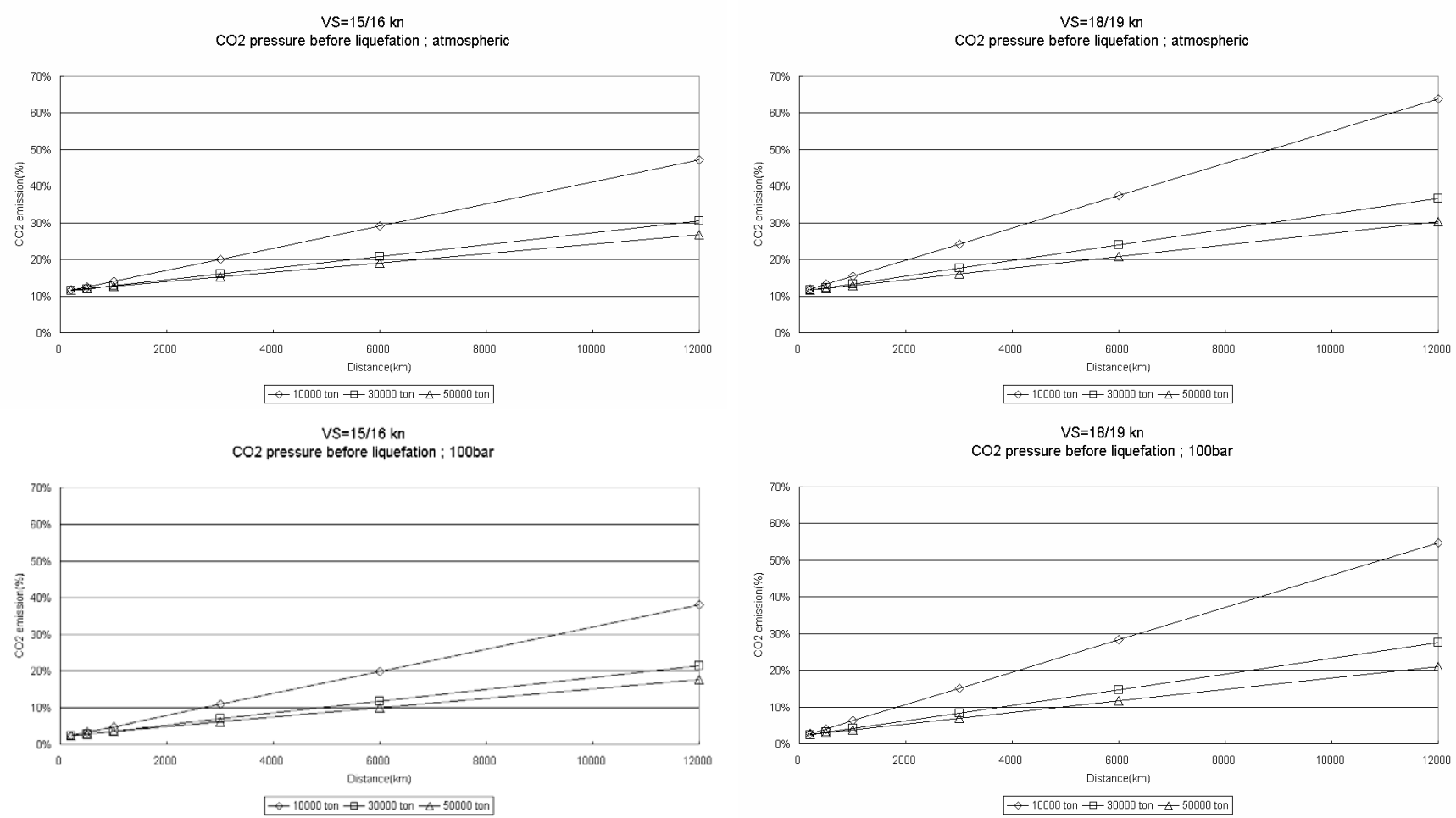


Fig.5-14 CO_2 emission

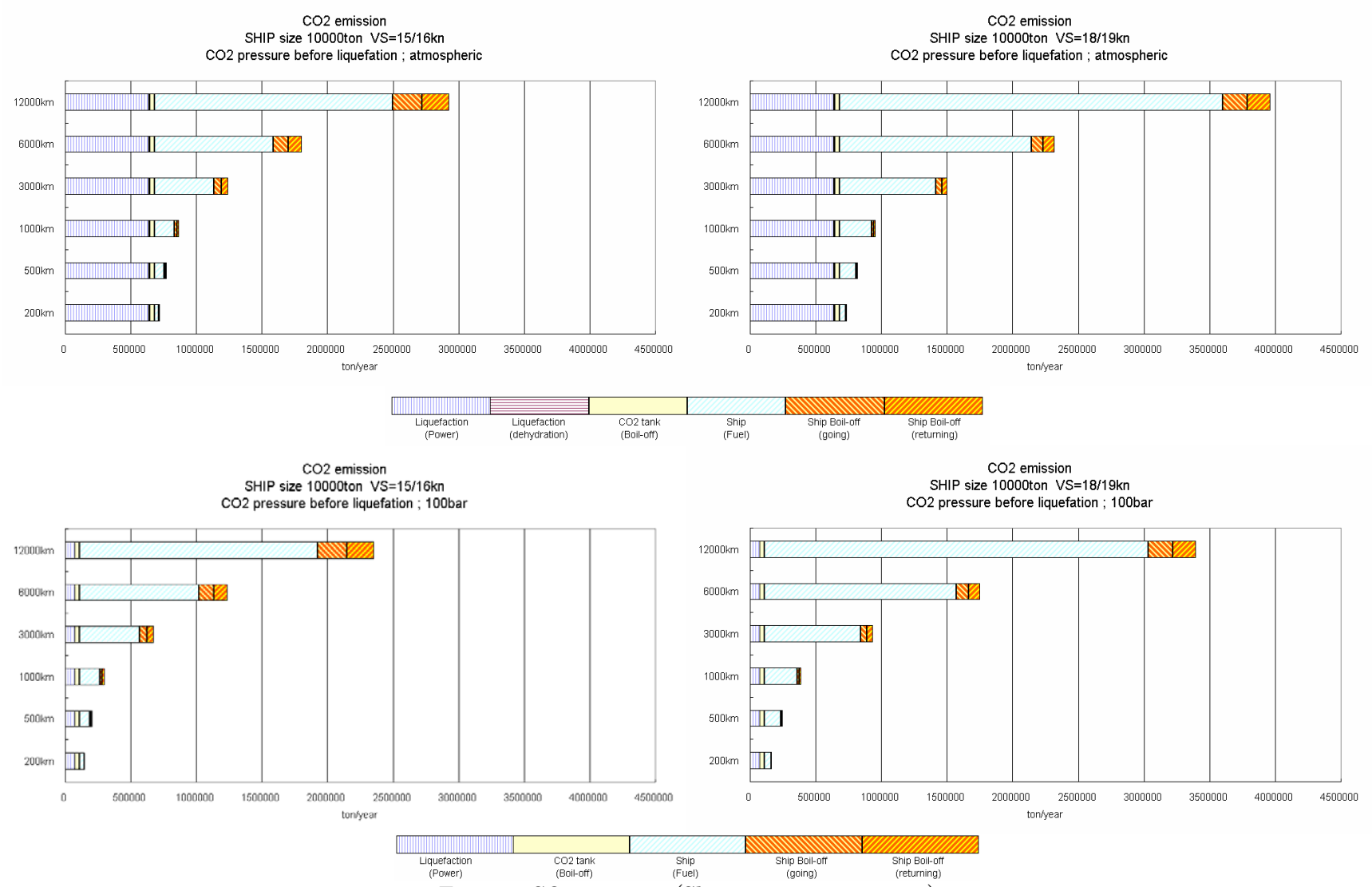


Fig.5-15 CO_2 emission (Ship size =10,000 tonne)

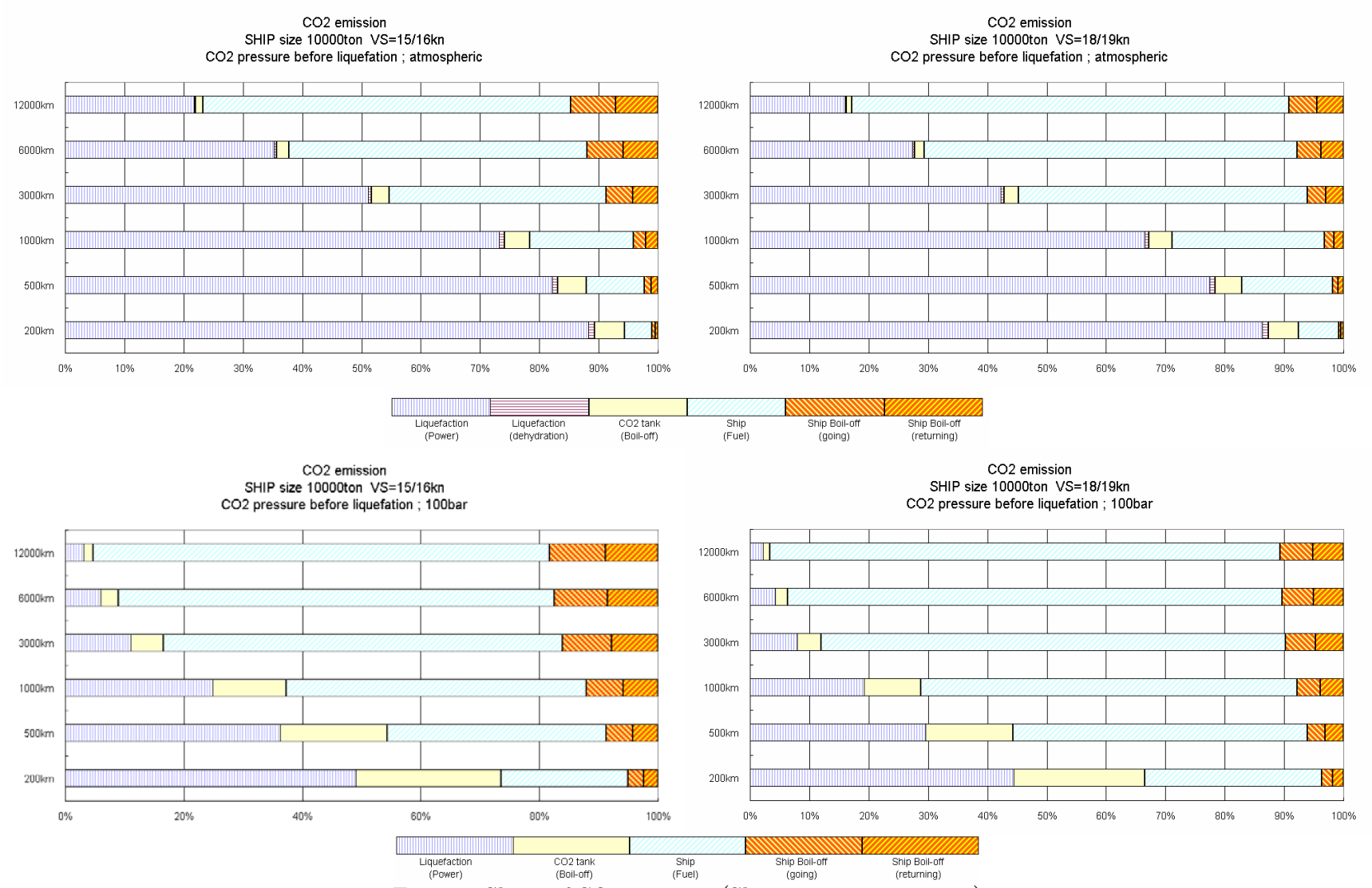


Fig.5-16 Share of CO_2 emission (Ship size =10,000 tonne)

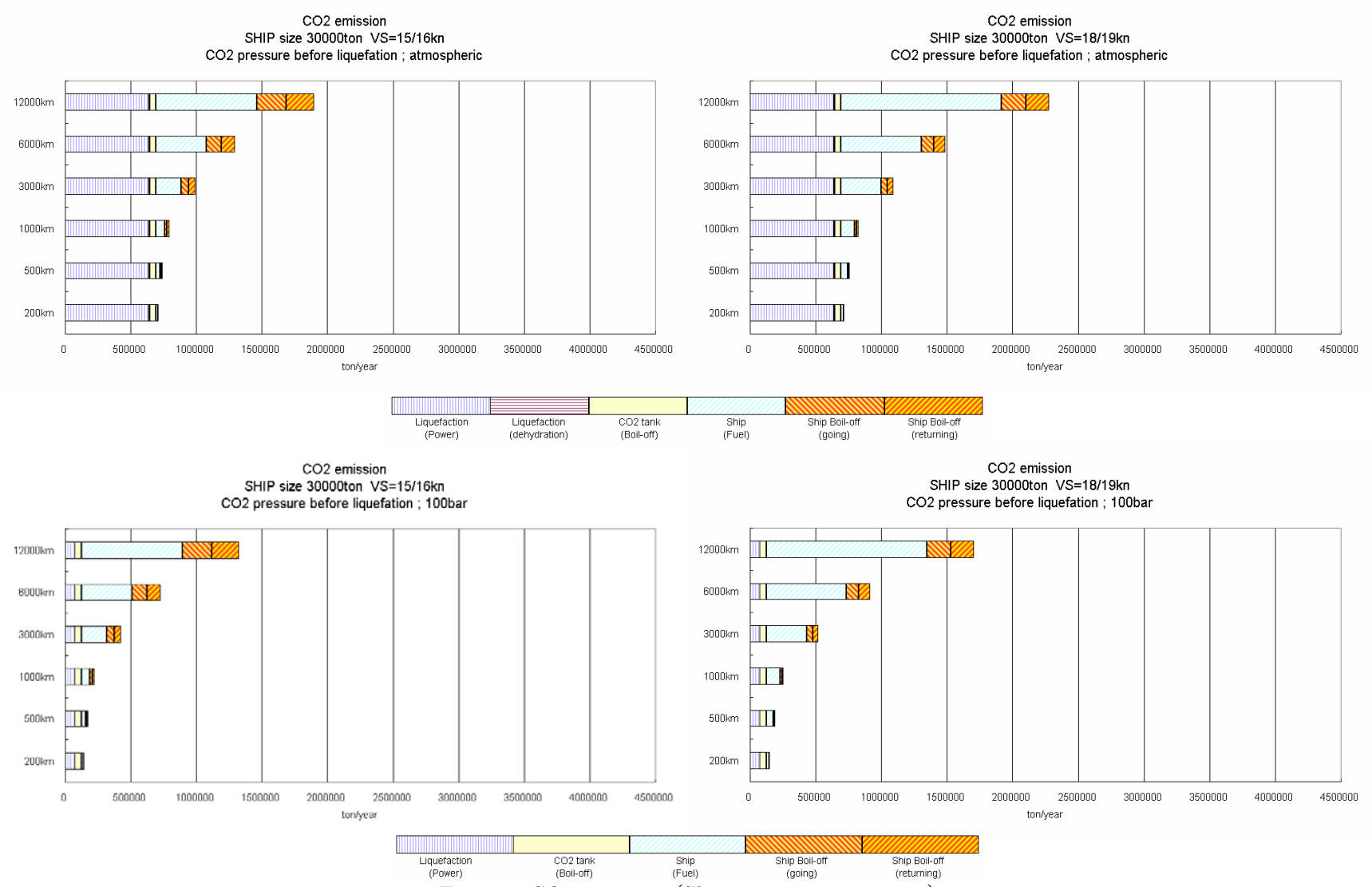


Fig.5-17 CO_2 emission (Ship size =30,000 tonne)

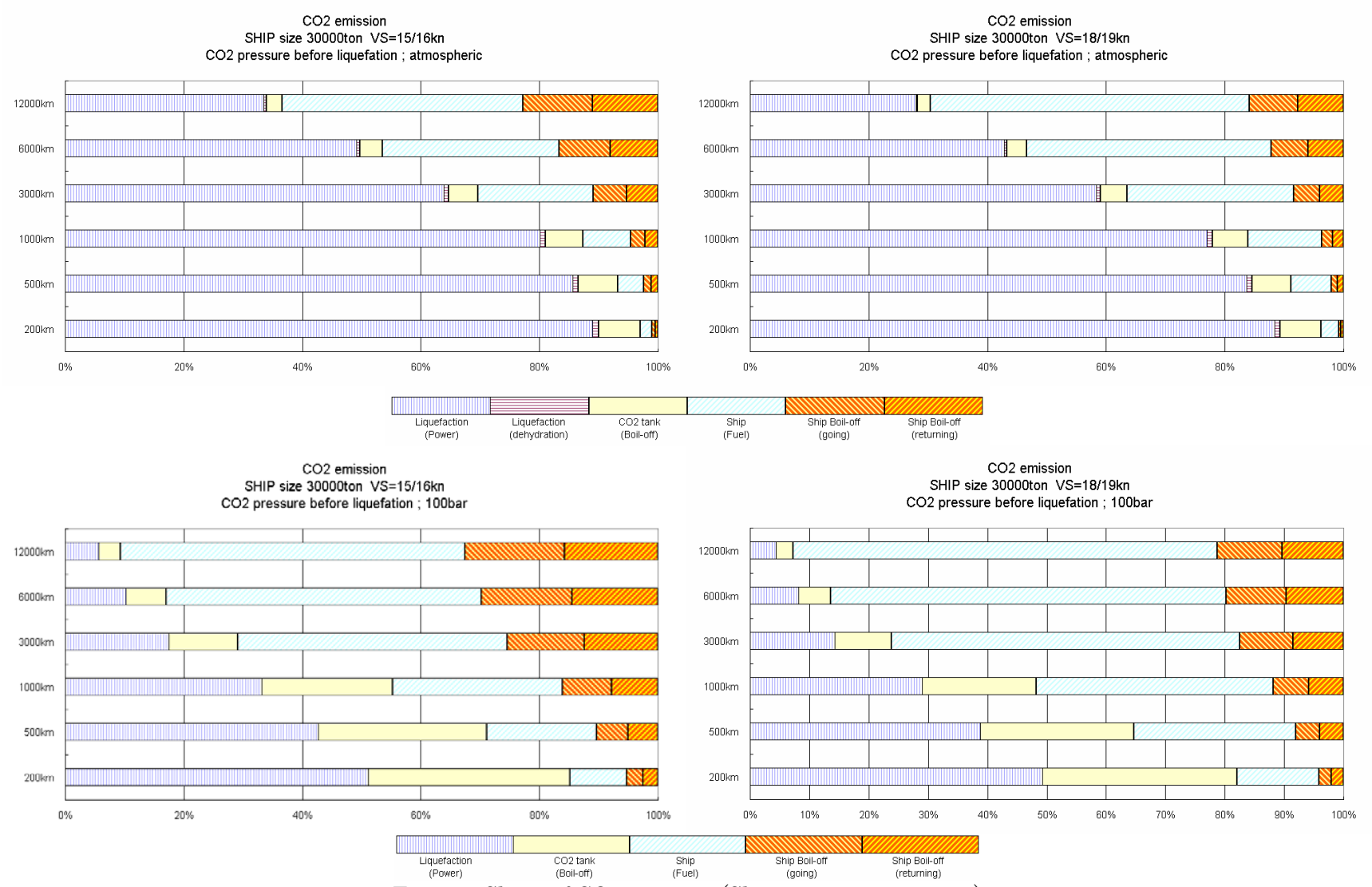


Fig.5-18 Share of CO_2 emission (Ship size =30,000 tonne)

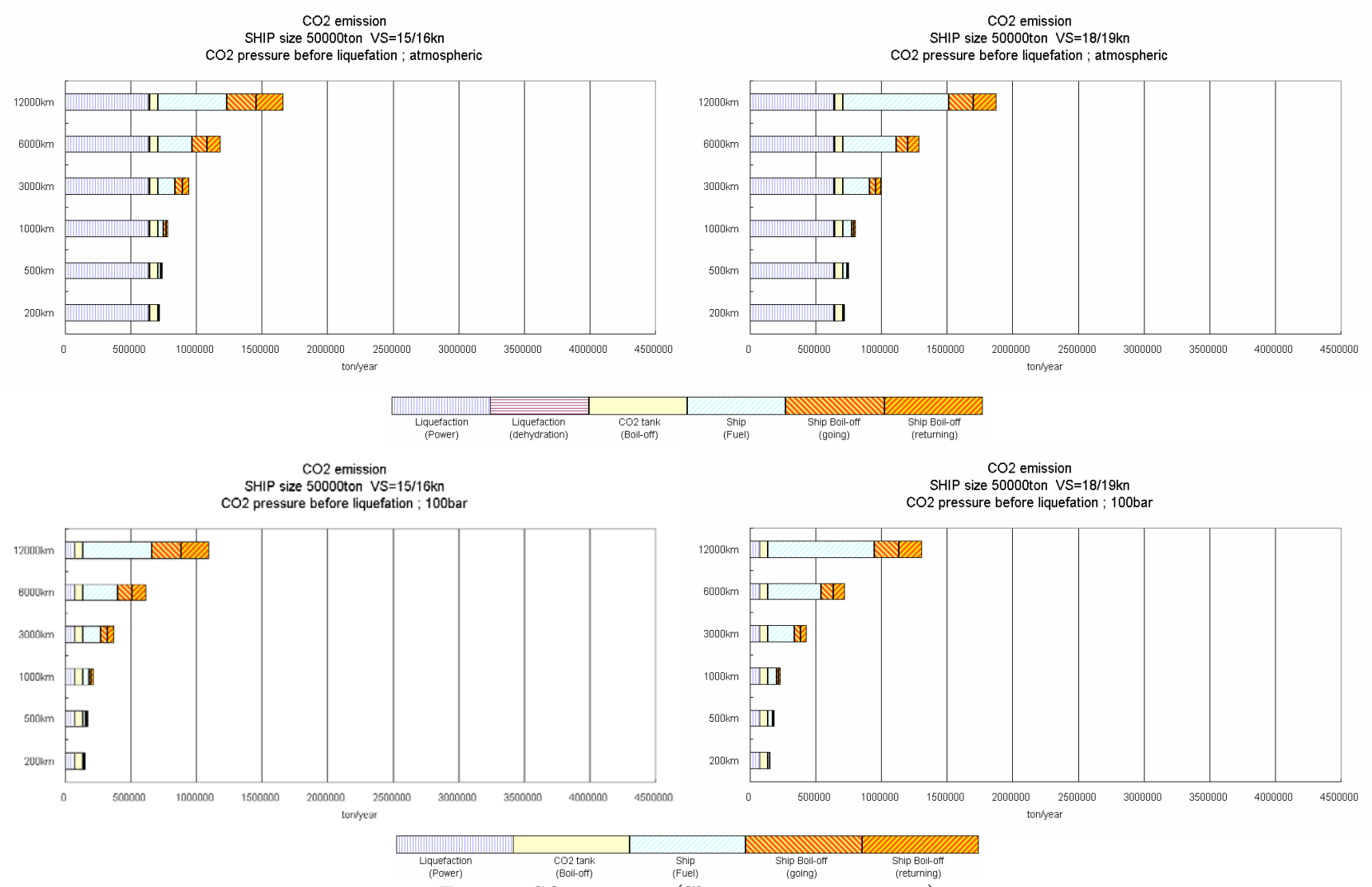


Fig.5-19 CO_2 emission (Ship size =50,000 tonne)

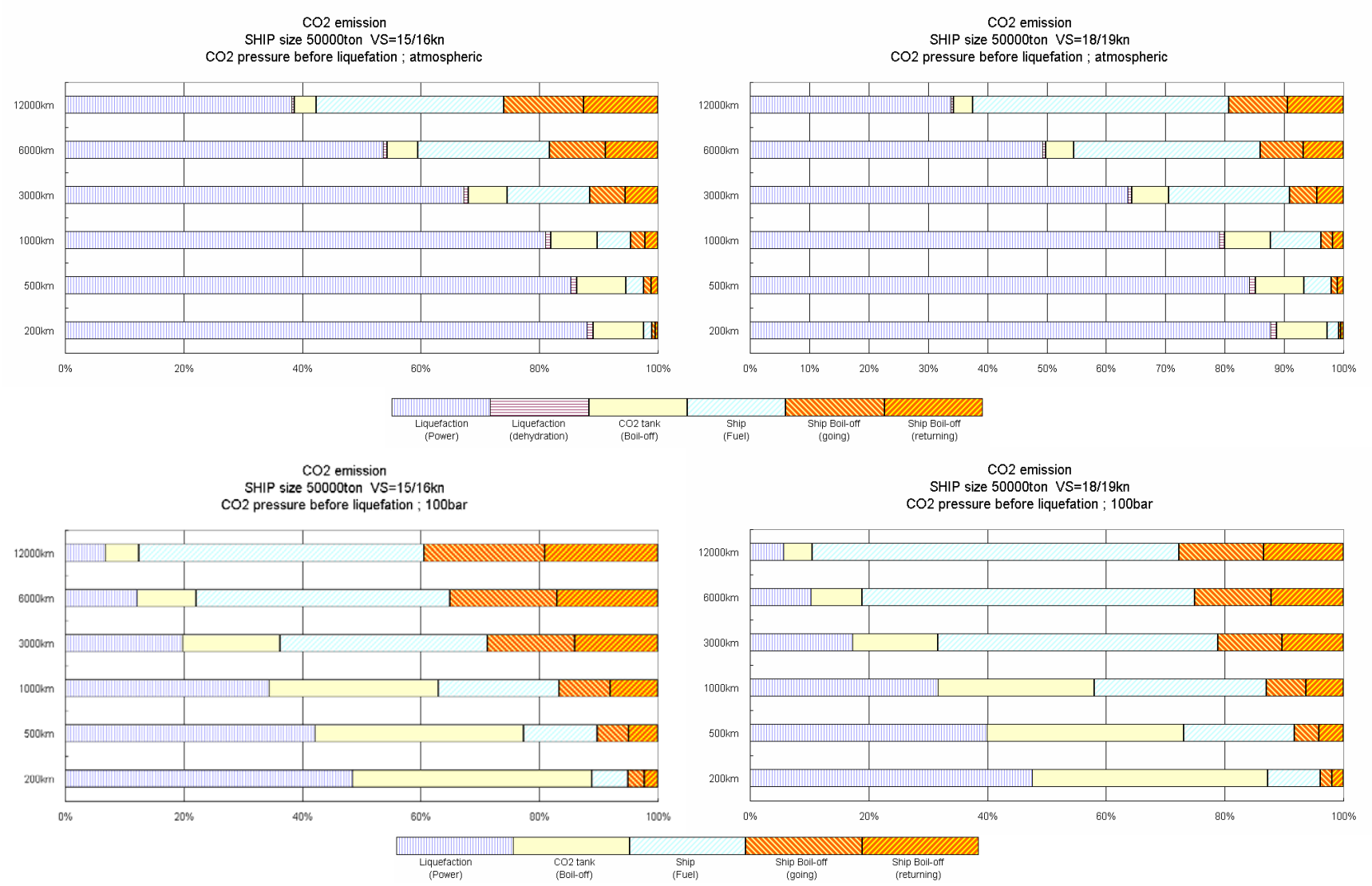
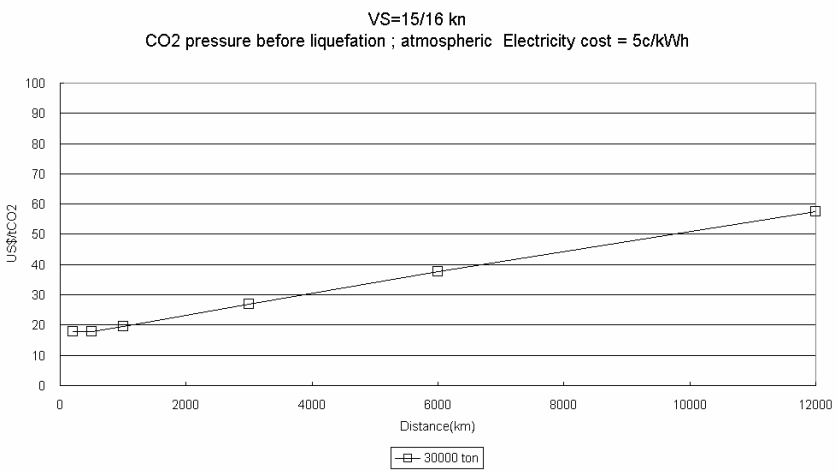
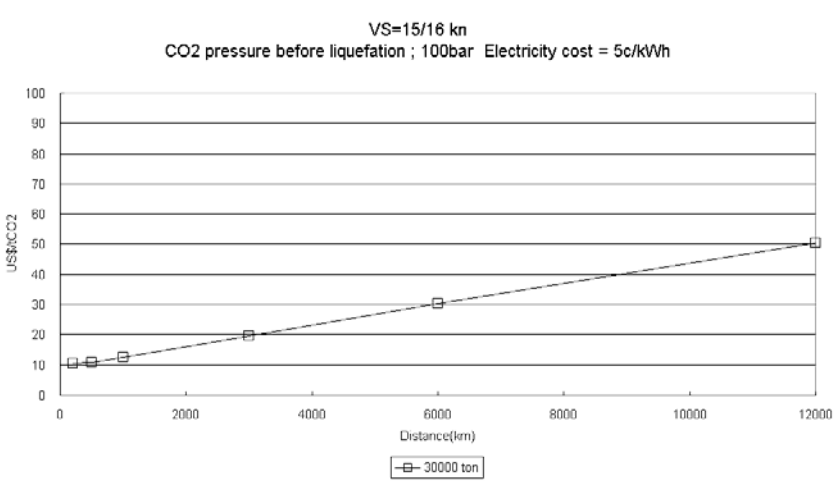


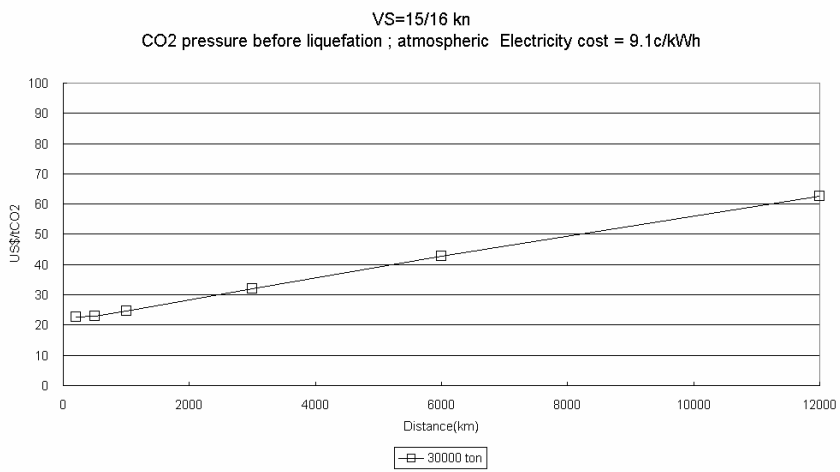
Fig.5-20 Share of CO_2 emission (Ship size =50,000 tonne)

Electricity cost = 5c/kWh





Electricity cost = 9.1c/kWh



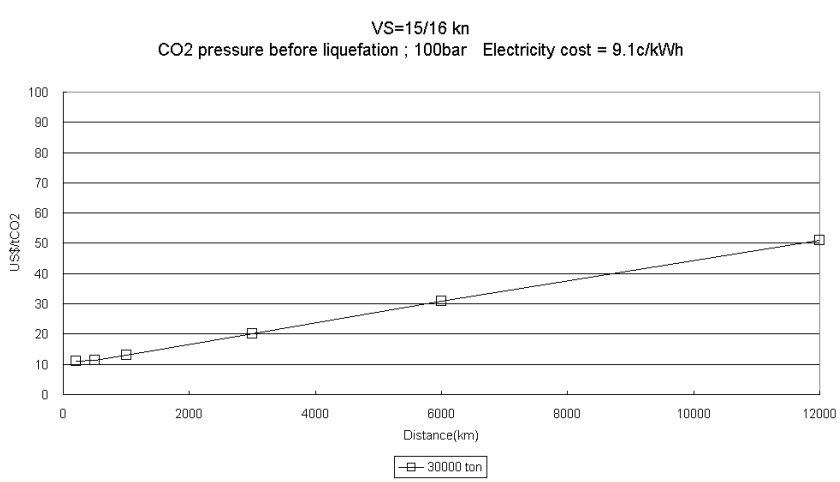
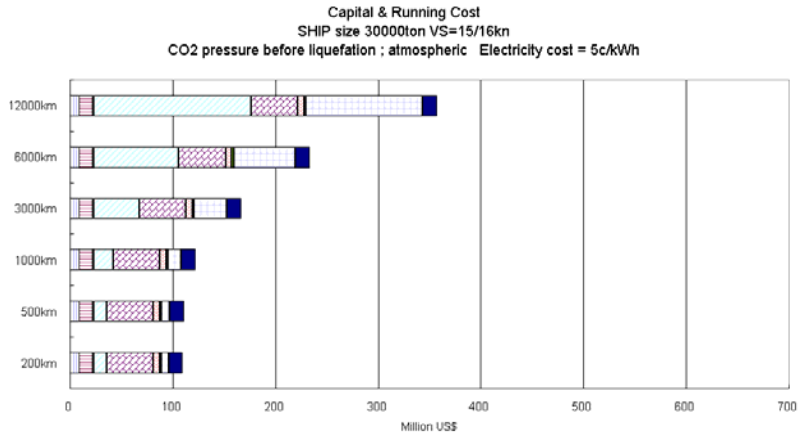
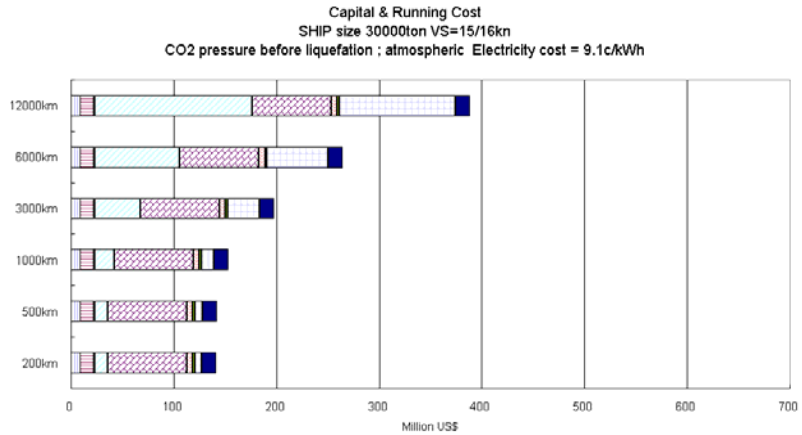


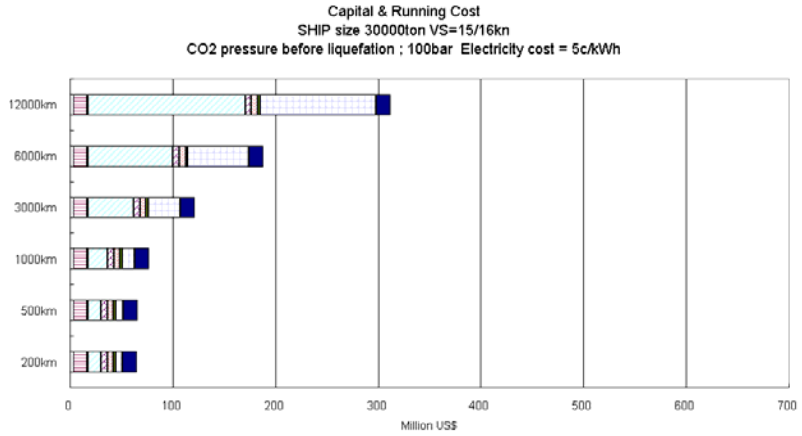
Fig.5-21 Impact of electricity cost for liquefaction on total cost (Capital and running)

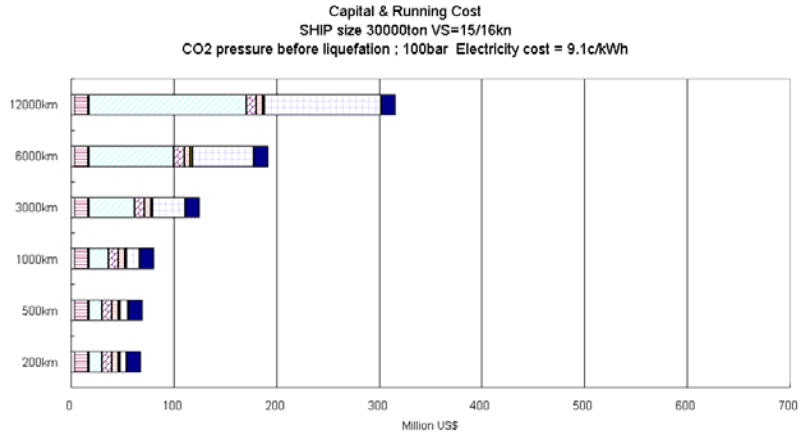
Electricity cost = 5c/kWh



Electricity cost = 9.1c/kWh







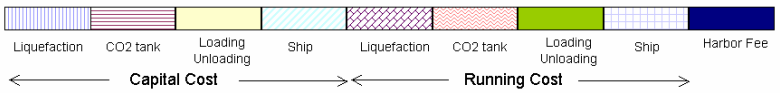
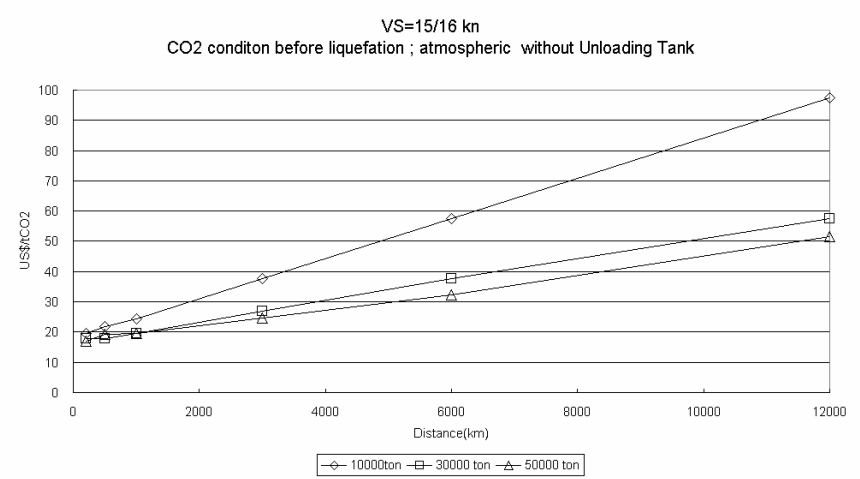


Fig.5-22 Impact of electricity cost for liquefaction on capital and running cost

Without unloading tank



With unloading tank

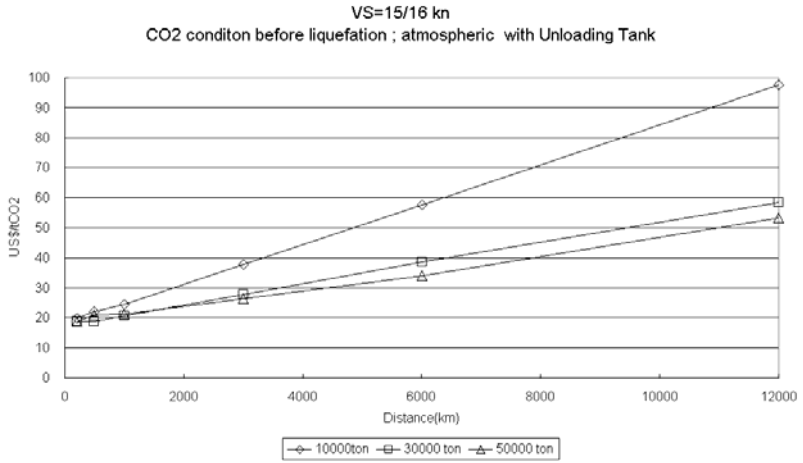


Fig.5-23 Cost impact of unloading tank

Without unloading tank

With unloading tank

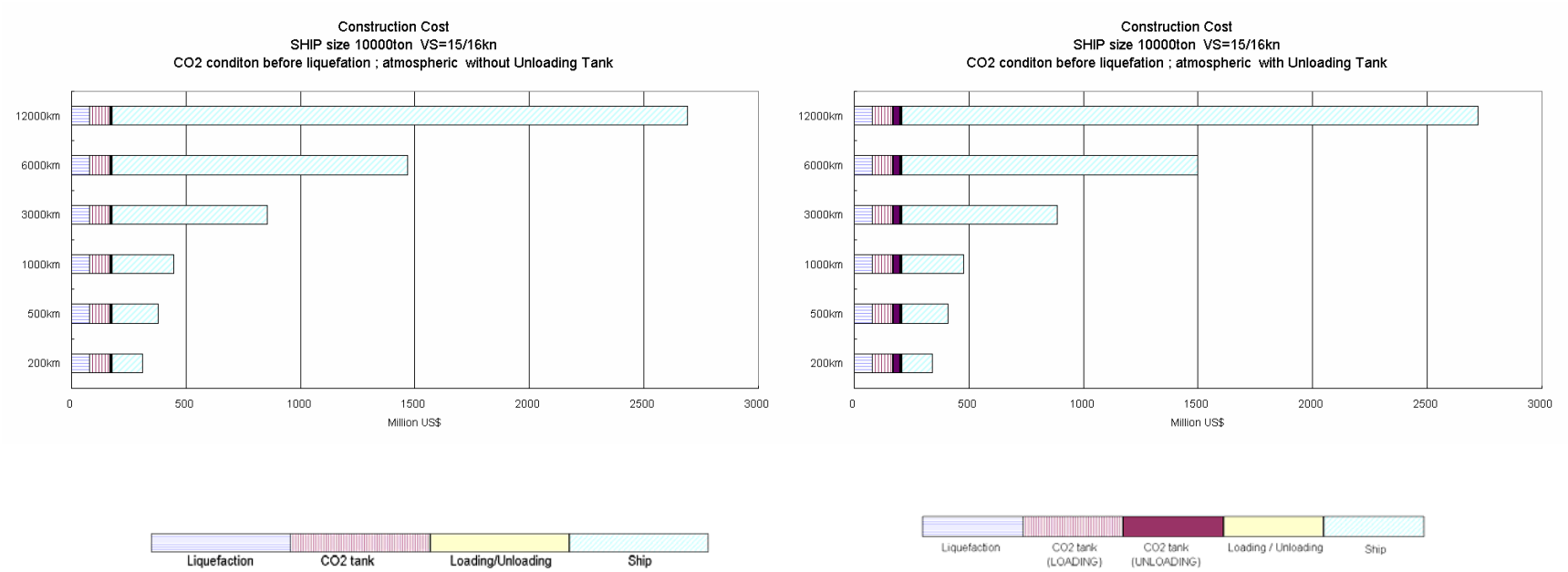


Fig.5-24 Impact of unloading tank on construction cost (Ship size =10,000 tonne)

Without unloading tank

With unloading tank

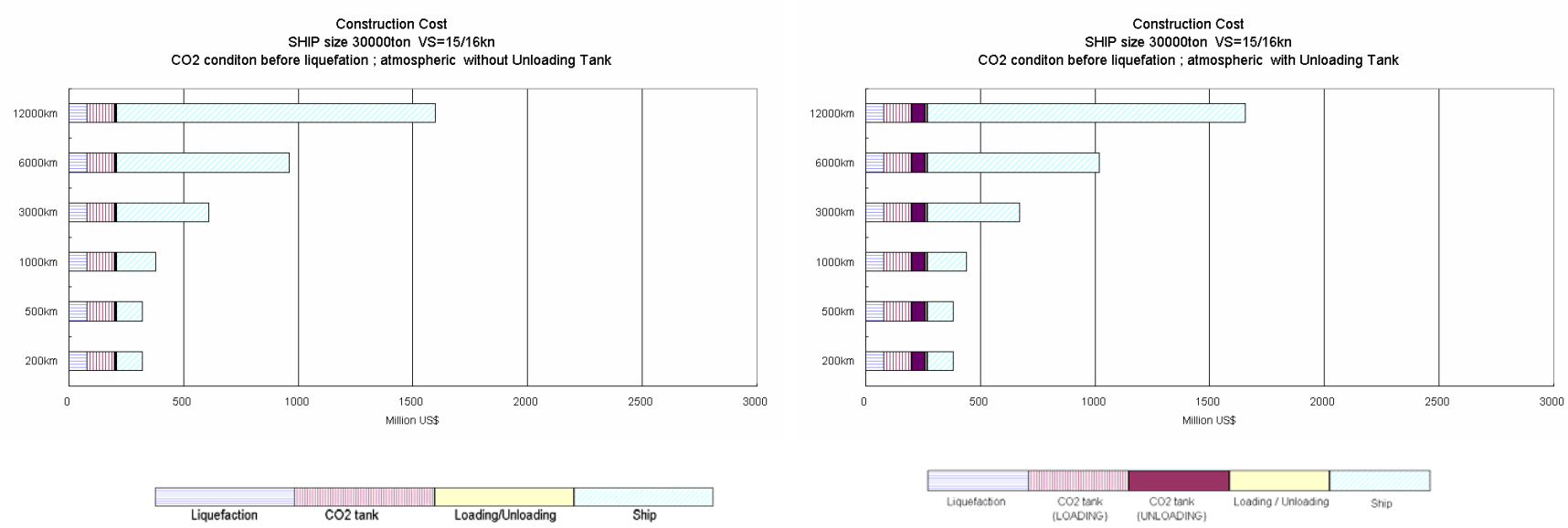


Fig.5-25 Impact of unloading tank on construction cost (Ship size =30,000 tonne)

Without unloading tank

With unloading tank

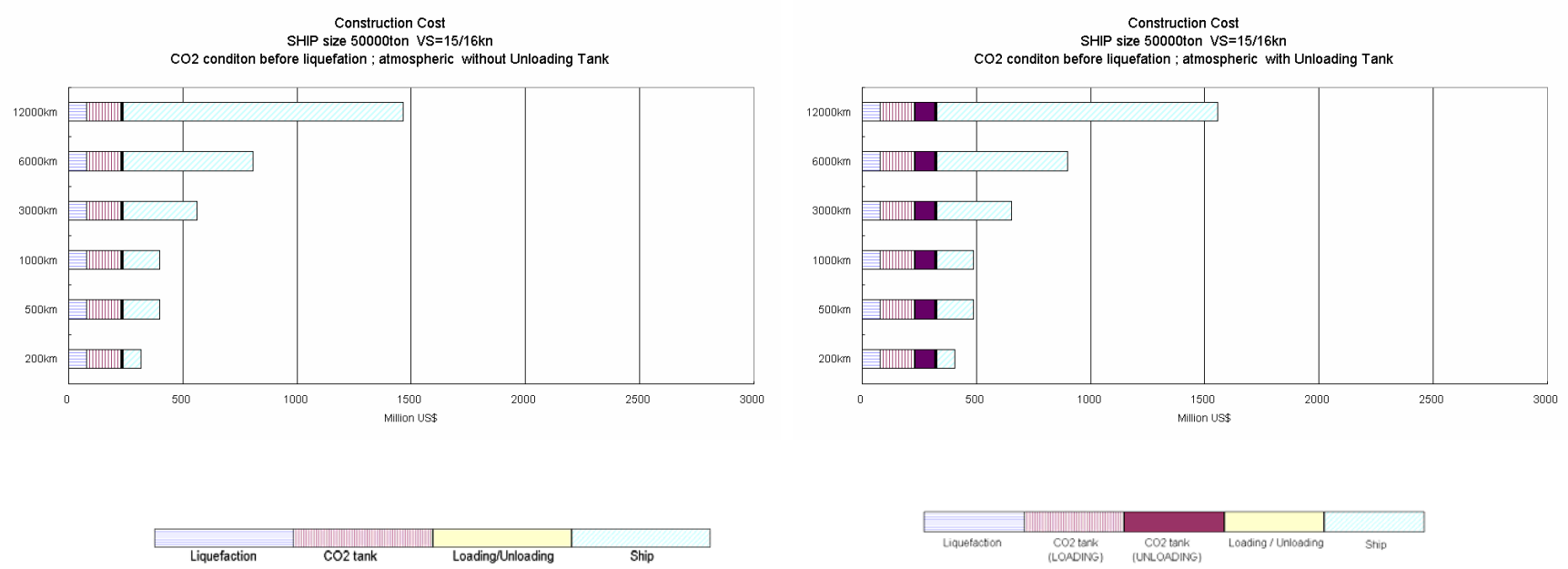
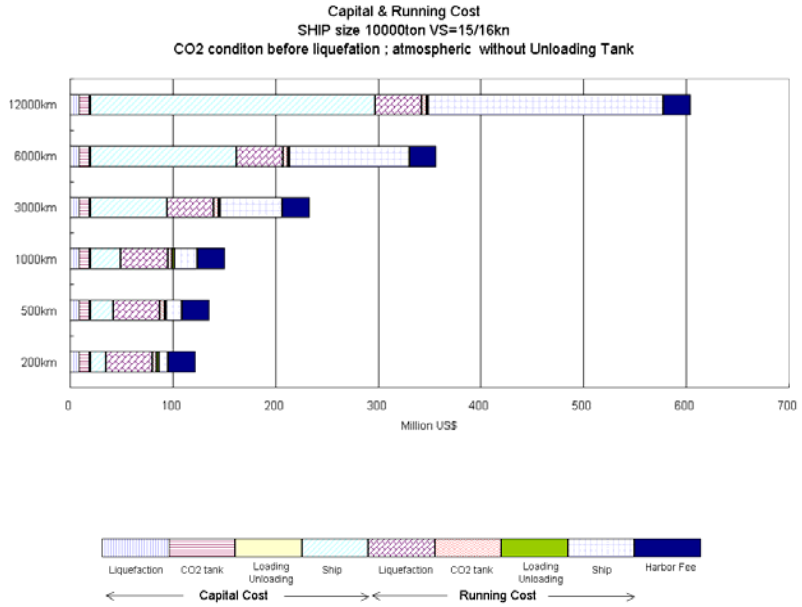


Fig.5-26 Impact of unloading tank on construction cost (Ship size =50,000 tonne)

Without unloading tank



With unloading tank

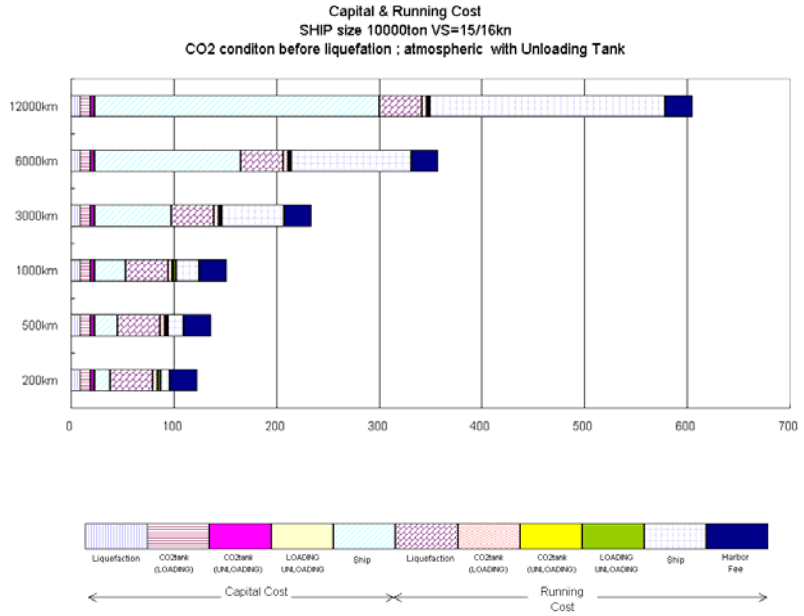
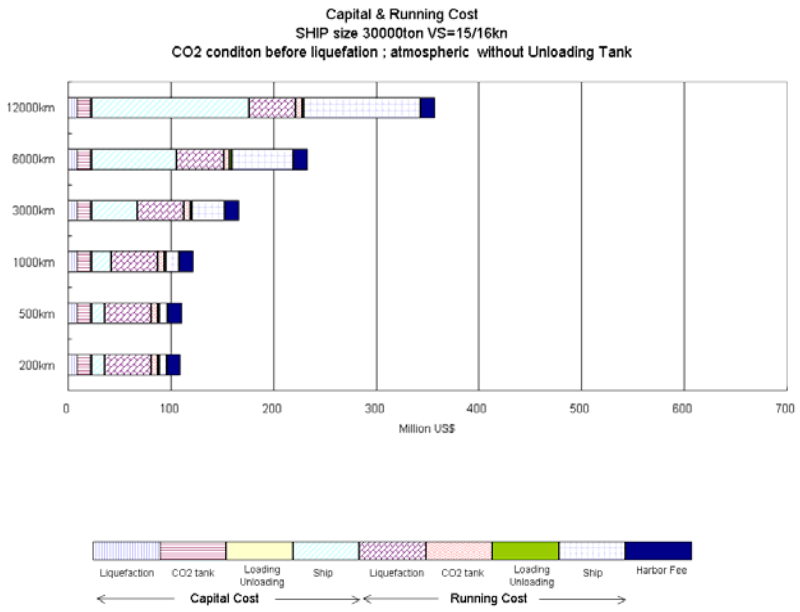


Fig.5-27 Impact of unloading tank on capital and running cost (Ship size =10,000 tonne)

Without unloading tank



With unloading tank

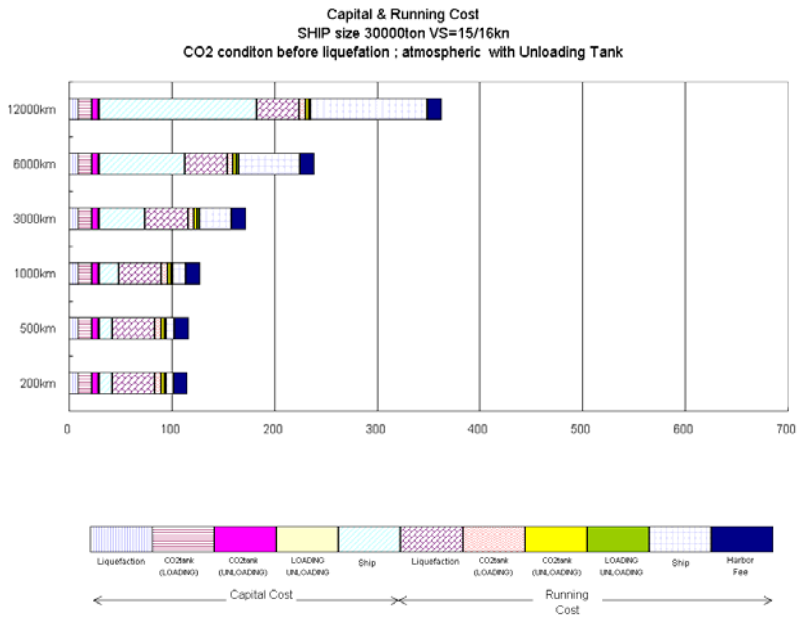


Fig.5-28 Impact of unloading tank on capital and running cost (Ship size =30,000 tonne)

Without unloading tank

With unloading tank

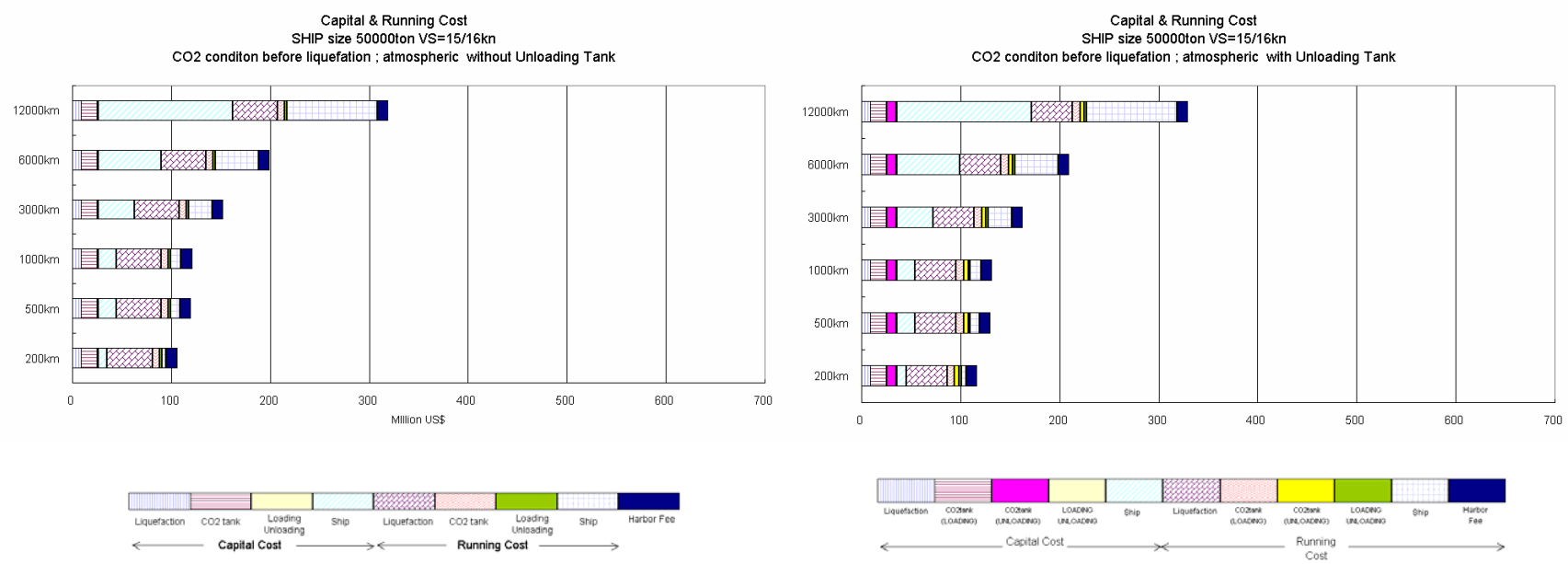


Fig.5-29 Impact of unloading tank on capital and running cost (Ship size =50,000 tonne)

Appendix.

Schedule of Shipping

Day		1						2						3						4						5					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	10,000			LOAD		8h				UNLOAD		7h				LOAD		8h				UNLOAD		7h				LOAD		8h	
SHIP2	10,000			LOAD		8h				UNLOAD		7h				LOAD		8h				UNLOAD		7h				LOAD		8h	
SHIP3	10,000									LOAD		8h				UNLOAD		7h				LOAD		8h				UNLOAD		7h	
SHIP4	10,000									LOAD		8h				UNLOAD		7h				LOAD		8h				UNLOAD		7h	
CO2(ton)	TANK	20000						20000						20000						20000						20000					
	LOAD	20000						20000						20000						20000						20000					
		0						0						0						0						0					

Day		6						7						8						9						10					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	10,000			UNLOAD		7h				LOAD		8h				UNLOAD		7h				LOAD		8h				UNLOAD		7h	
SHIP2	10,000			UNLOAD		7h				LOAD		8h				UNLOAD		7h				LOAD		8h				UNLOAD		7h	
SHIP3	10,000			LOAD		8h				UNLOAD		7h				LOAD		8h				UNLOAD		7h				LOAD		8h	
SHIP4	10,000			LOAD		8h				UNLOAD		7h				LOAD		8h				UNLOAD		7h				LOAD		8h	
CO2(ton)	TANK	20000						20000						20000						20000						20000					
	LOAD	20000						20000						20000						20000						20000					
		0						0						0						0						0					

Schedule of Ship transportation ; 200km 10000tonne 15/16kn

Day		1						2						3						4						5					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	10,000			LOAD		6h				UNLOAD		6h				LOAD		6h				UNLOAD		6h				LOAD		6h	
SHIP2	10,000			LOAD		6h				UNLOAD		6h				LOAD		6h				UNLOAD		6h				LOAD		6h	
SHIP3	10,000									LOAD		6h				UNLOAD		6h				LOAD		6h				UNLOAD		6h	
SHIP4	10,000									LOAD		6h				UNLOAD		6h				LOAD		6h				UNLOAD		6h	
CO2(ton)	TANK	20000						20000						20000						20000						20000					
	LOAD	20000						20000						20000						20000						20000					
		0						0						0						0						0					

Day		6						7						8						9						10					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	10,000			UNLOAD		6h				LOAD		6h				UNLOAD		6h				LOAD		6h				UNLOAD		6h	
SHIP2	10,000			UNLOAD		6h				LOAD		6h				UNLOAD		6h				LOAD		6h				UNLOAD		6h	
SHIP3	10,000			LOAD		6h				UNLOAD		6h				LOAD		6h				UNLOAD		6h				LOAD		6h	
SHIP4	10,000			LOAD		6h				UNLOAD		6h				LOAD		6h				UNLOAD		6h				LOAD		6h	
CO2(ton)	TANK	20000						20000						20000						20000						20000					
	LOAD	20000						20000						20000						20000						20000					
		0						0						0						0						0					

Schedule of Ship transportation ; 200km 10000tonne 18/19kn

Day		1						2						3						4						5					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	30,000			LOAD			8h			UNLOAD			7h									LOAD			8h					UNLOAD			7h
SHIP2	30,000															LOAD			8h			UNLOAD			7h						
CO2(ton)	TANK	30000						20000						40000						30000						20000					
	LOAD	30000						0						30000						30000						0					
		0						20000						10000						0						20000					

Day		6						7						8						9						10					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	30,000									LOAD			8h			UNLOAD			7h									LOAD			8h
SHIP2	30,000			LOAD			8h			UNLOAD			7h									LOAD			8h			UNLOAD			7h
CO2(ton)	TANK	40000						30000						20000						40000						30000					
	LOAD	30000						30000						0						30000						30000					
		10000						0						20000						10000						0					

Schedule of Ship transportation ; 200km 30000tonne 15/16kn

Day		1						2						3						4						5					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	30,000			LOAD			6h			UNLOAD			6h									LOAD			6h					UNLOAD			6h
SHIP2	30,000															LOAD			6h			UNLOAD			6h						
CO2(ton)	TANK	30000						20000						40000						30000						20000					
	LOAD	30000						0						30000						30000						0					
		0						20000						10000						0						20000					

Day		6						7						8						9						10					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	30,000									LOAD			6h			UNLOAD			6h									LOAD			6h
SHIP2	30,000			LOAD			6h			UNLOAD			6h									LOAD			6h			UNLOAD			6h
CO2(ton)	TANK	40000						30000						20000						40000						30000					
	LOAD	30000						30000						0						30000						30000					
		10000						0						20000						10000						0					

Schedule of Ship transportation ; 200km 30000tonne 18/19kn

Day		1						2						3						4						5					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	50,000			LOAD		8h				UNLOAD		7h										LOAD		8h				UNLOAD		7h	
CO2(ton)	TANK	50000						20000						40000						60000						30000					
	LOAD	50000						0						0						50000						0					
		0						20000						40000						10000						30000					

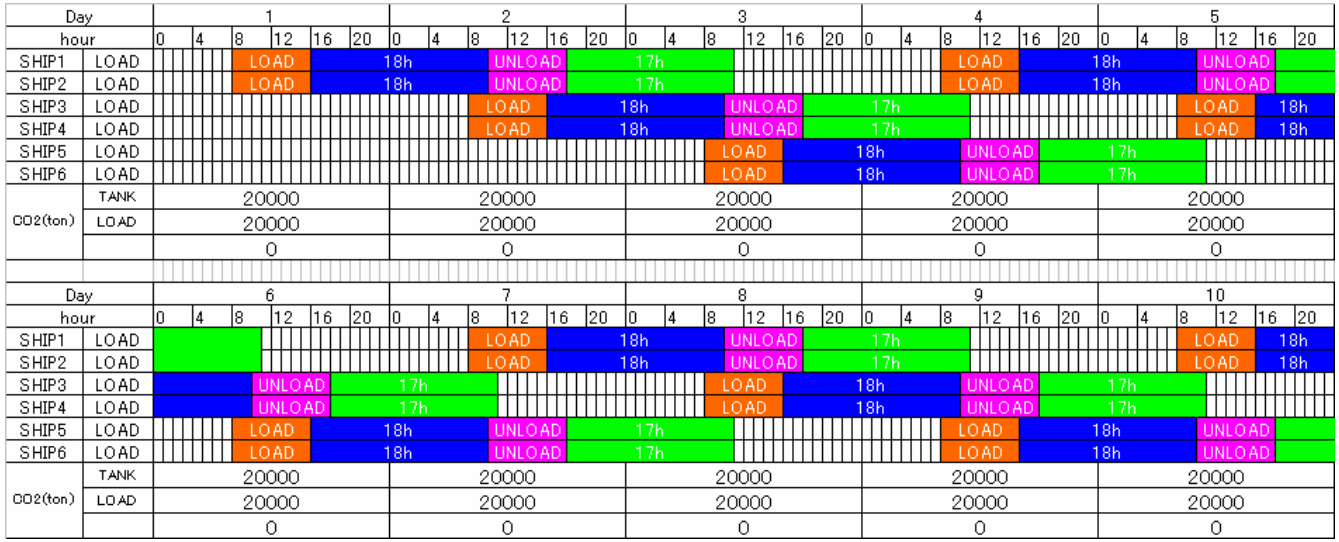
Day		6						7						8						9						10					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	50,000			LOAD		8h				UNLOAD		7h										LOAD		8h				UNLOAD		7h	
CO2(ton)	TANK	50000						20000						40000						60000						30000					
	LOAD	50000						0						0						50000						0					
		0						20000						40000						10000						30000					

Schedule of Ship transportation ; 200km 50000tonne 15/16kn

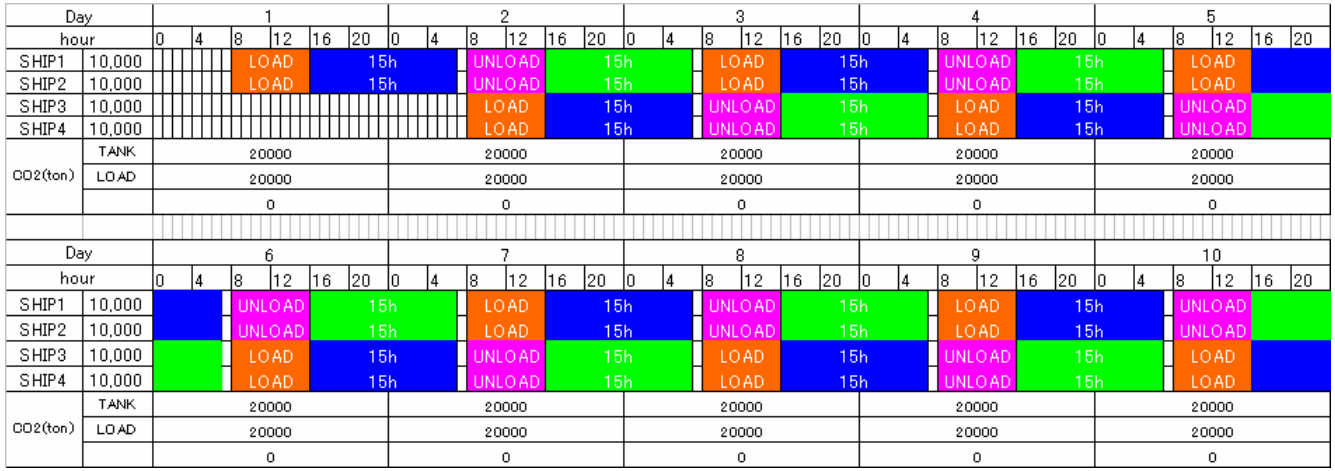
Day		1						2						3						4						5					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	50,000			LOAD		6h				UNLOAD		6h										LOAD		6h				UNLOAD		6h	
CO2(ton)	TANK	50000						20000						40000						60000						30000					
	LOAD	50000						0						0						50000						0					
		0						20000						40000						10000						30000					

Day		6						7						8						9						10					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	50,000			LOAD		6h				UNLOAD		6h										LOAD		6h				UNLOAD		6h	
CO2(ton)	TANK	50000						20000						40000						60000						30000					
	LOAD	50000						0						0						50000						0					
		0						20000						40000						10000						30000					

Schedule of Ship transportation ; 200km 50000tonne 18/19kn



Schedule of Ship transportation ; 500km 10000tonne 15/16kn



Schedule of Ship transportation ; 500km 10000tonne 18/19kn

Day		1						2						3						4						5					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	30,000			LOAD		18h				UNLOAD		17h																			
SHIP2	30,000															LOAD		18h				UNLOAD		17h							
CO2(ton)	TANK	30000						20000						40000						30000						20000					
	LOAD	30000						0						30000						30000						0					
		0						20000						10000						0						20000					

Day		6						7						8						9						10					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	30,000									LOAD		18h				UNLOAD		17h										LOAD			
SHIP2	30,000			LOAD		18h				UNLOAD		17h										LOAD		18h				UNLOAD		17h	
CO2(ton)	TANK	40000						30000						20000						40000						30000					
	LOAD	30000						30000						0						30000						30000					
		10000						0						20000						10000						0					

Schedule of Ship transportation ; 500km 30000tonne 15/16kn

Day		1						2						3						4						5					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	30,000			LOAD		15h				UNLOAD		15h										LOAD		15h				UNLOAD			
SHIP2	30,000															LOAD		15h				UNLOAD		15h							
CO2(ton)	TANK	30000						20000						40000						30000						20000					
	LOAD	30000						0						30000						30000						0					
		0						20000						10000						0						20000					

Day		6						7						8						9						10					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	30,000									LOAD		15h				UNLOAD		15h										LOAD			
SHIP2	30,000			LOAD		15h				UNLOAD		15h										LOAD		15h				UNLOAD			
CO2(ton)	TANK	40000						30000						20000						40000						30000					
	LOAD	30000						30000						0						30000						30000					
		10000						0						20000						10000						0					

Schedule of Ship transportation ; 500km 30000tonne 18/19kn

Day		1						2						3						4						5					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	50,000			LOAD				18h						UNLOAD						17h											
SHIP2	50,000																					LOAD				18h				UNLOAD	
CO2(ton)	TANK	50000						20000						40000						60000						30000					
	LOAD	50000						0						0						50000						0					
		0						20000						40000						10000						30000					

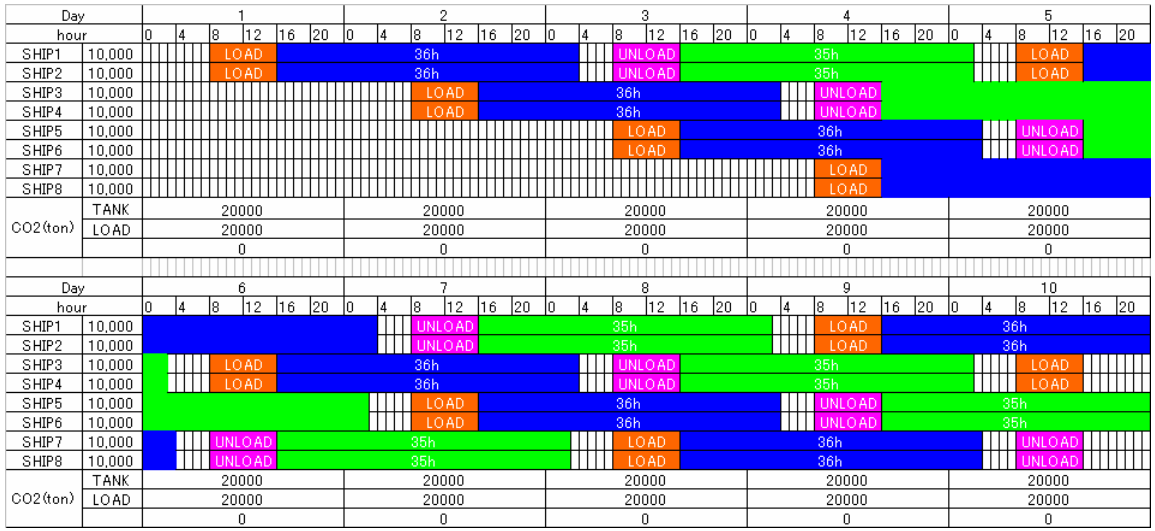
Day		6						7						8						9						10					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	50,000			LOAD				18h						UNLOAD						17h											
SHIP2	50,000																					LOAD				18h				UNLOAD	17h
CO2(ton)	TANK	50000						20000						40000						60000						30000					
	LOAD	50000						0						0						50000						0					
		0						20000						40000						10000						30000					

Schedule of Ship transportation ; 500km 50000tonne 15/16kn

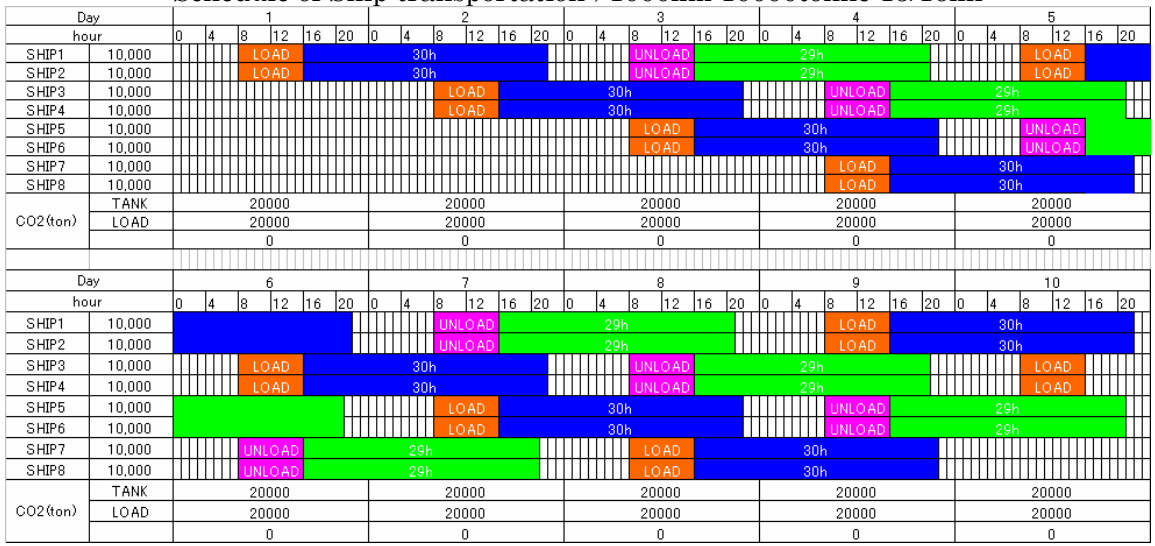
Day		1						2						3						4						5					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	30,000			LOAD				15h						UNLOAD						15h											
SHIP2	30,000																					LOAD				15h				UNLOAD	
CO2(ton)	TANK	50000						20000						40000						60000						30000					
	LOAD	50000						0						0						50000						0					
		0						20000						40000						10000						30000					

Day		6						7						8						9						10					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	30,000			LOAD				15h						UNLOAD						15h											
SHIP2	30,000																					LOAD				15h					
CO2(ton)	TANK	50000						20000						40000						60000						30000					
	LOAD	50000						0						0						50000						0					
		0						20000						40000						10000						30000					

Schedule of Ship transportation ; 500km 50000tonne 18/19kn



Schedule of Ship transportation ; 1000km 10000tonne 15/16kn



Schedule of Ship transportation ; 1000km 10000tonne 18/19kn

Day		1						2						3						4						5					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	30,000			LOAD				36h								UNLOAD				35h												
SHIP2	30,000															LOAD				36h								UNLOAD			
SHIP3	30,000																			LOAD											
CO2(ton)	TANK	30000						20000						40000						30000						20000					
	LOAD	30000						0						30000						30000						0					
		0						20000						10000						0						20000					

Day		6						7						8						9						10					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	30,000			LOAD				36h						UNLOAD						35h								LOAD			
SHIP2	30,000								LOAD					36h						UNLOAD						35h					
SHIP3	30,000			UNLOAD				35h												LOAD						36h					
CO2(ton)	TANK	40000						30000						20000						40000						30000					
	LOAD	30000						30000						0						30000						30000					
		10000						0						20000						10000						0					

Schedule of Ship transportation ; 1000km 30000tonne 15/16kn

Day		1						2						3						4						5					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	30,000			LOAD				30h								UNLOAD				29h												
SHIP2	30,000															LOAD				30h								UNLOAD			
SHIP3	30,000																			LOAD						30h					
CO2(ton)	TANK	30000						20000						40000						30000						20000					
	LOAD	30000						0						30000						30000						0					
		0						20000						10000						0						20000					

Day		6						7						8						9						10					
hour		0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20	0	4	8	12	16	20
SHIP1	30,000			LOAD				30h						UNLOAD						29h								LOAD			
SHIP2	30,000								LOAD					30h						UNLOAD						29h					
SHIP3	30,000			UNLOAD				29h												LOAD						30h					
CO2(ton)	TANK	40000						30000						20000						40000						30000					
	LOAD	30000						30000						0						30000						30000					
		10000						0						20000						10000						0					

Schedule of Ship transportation ; 1000km 30000tonne 18/19kn

Day		1	2	3	4	5
hour		0 4 8 12 16 20	0 4 8 12 16 20	0 4 8 12 16 20	0 4 8 12 16 20	0 4 8 12 16 20
SHIP1	50,000	LOAD	36h	UNLOAD	35h	
SHIP2	50,000				LOAD	
CO2(ton)	TANK	50000	20000	40000	60000	30000
	LOAD	50000	0	0	50000	0
		0	20000	40000	10000	30000

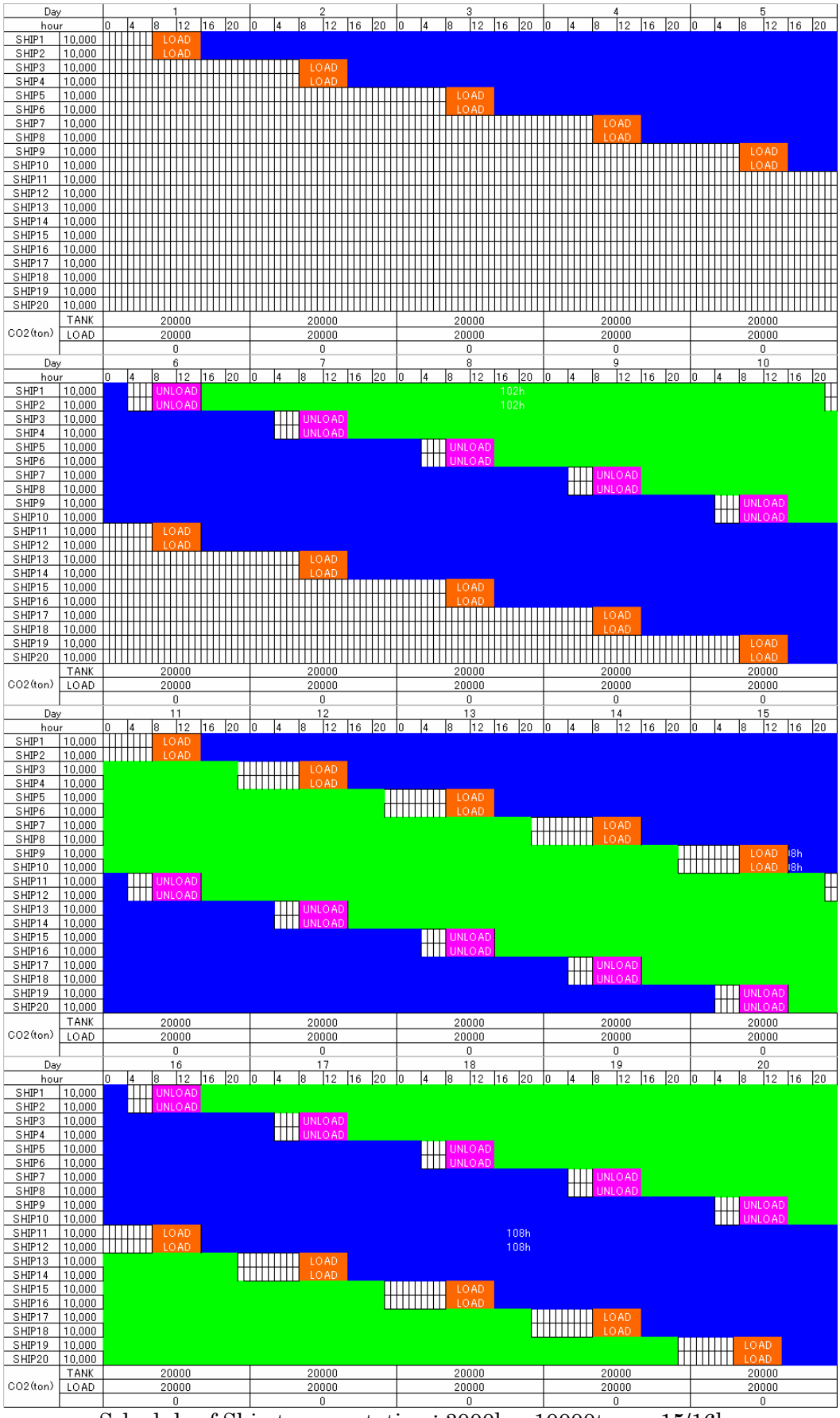
Day		6	7	8	9	10
hour		0 4 8 12 16 20	0 4 8 12 16 20	0 4 8 12 16 20	0 4 8 12 16 20	0 4 8 12 16 20
SHIP1	50,000	50000	36h	UNLOAD	35h	
SHIP2	50,000	UNLOAD	35h		50000	36h
CO2(ton)	TANK	50000	20000	40000	60000	30000
	LOAD	50000	0	0	50000	0
		0	20000	40000	10000	30000

Schedule of Ship transportation ; 1000km 50000tonne 15/16kn

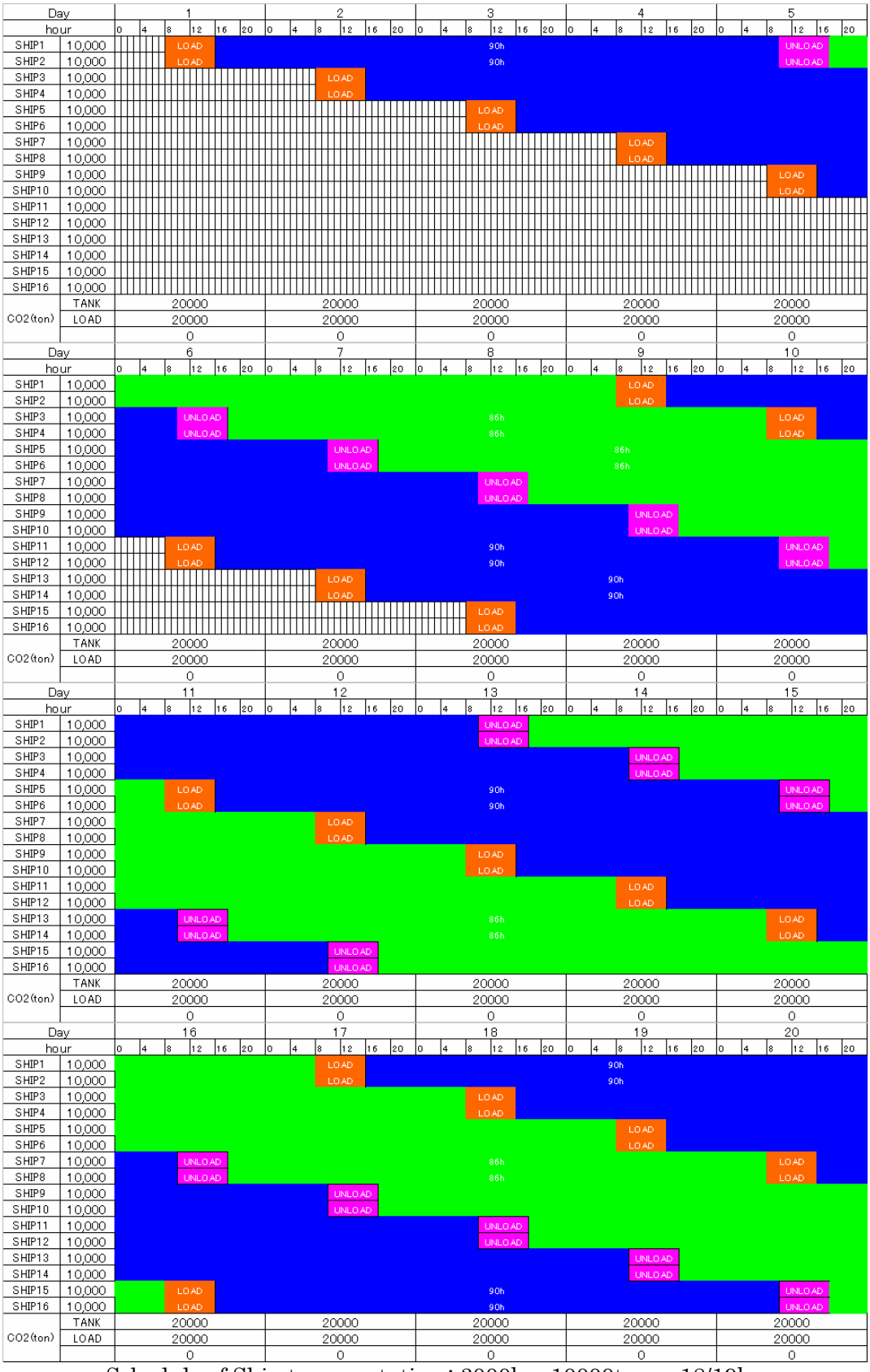
Day		1	2	3	4	5
hour		0 4 8 12 16 20	0 4 8 12 16 20	0 4 8 12 16 20	0 4 8 12 16 20	0 4 8 12 16 20
SHIP1	50,000	LOAD	30h	UNLOAD	29h	
SHIP2	50,000				LOAD	30h
CO2(ton)	TANK	50000	20000	40000	60000	30000
	LOAD	50000	0	0	50000	0
		0	20000	40000	10000	30000

Day		6	7	8	9	10
hour		0 4 8 12 16 20	0 4 8 12 16 20	0 4 8 12 16 20	0 4 8 12 16 20	0 4 8 12 16 20
SHIP1	50,000	LOAD	30h	UNLOAD	29h	
SHIP2	50,000	UNLOAD	29h		LOAD	30h
CO2(ton)	TANK	50000	20000	40000	60000	30000
	LOAD	50000	0	0	50000	0
		0	20000	40000	10000	30000

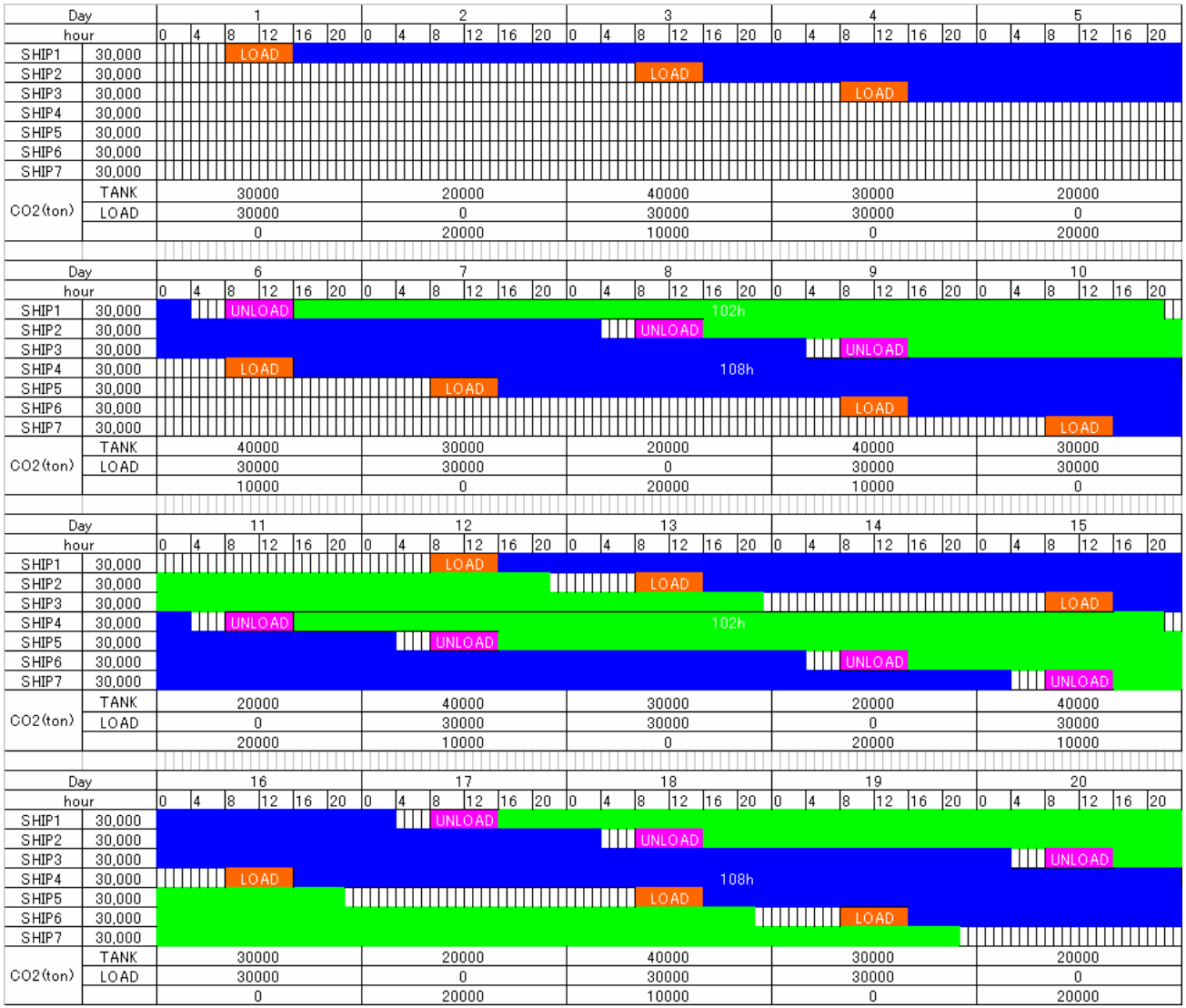
Schedule of Ship transportation ; 1000km 50000tonne 18/19kn



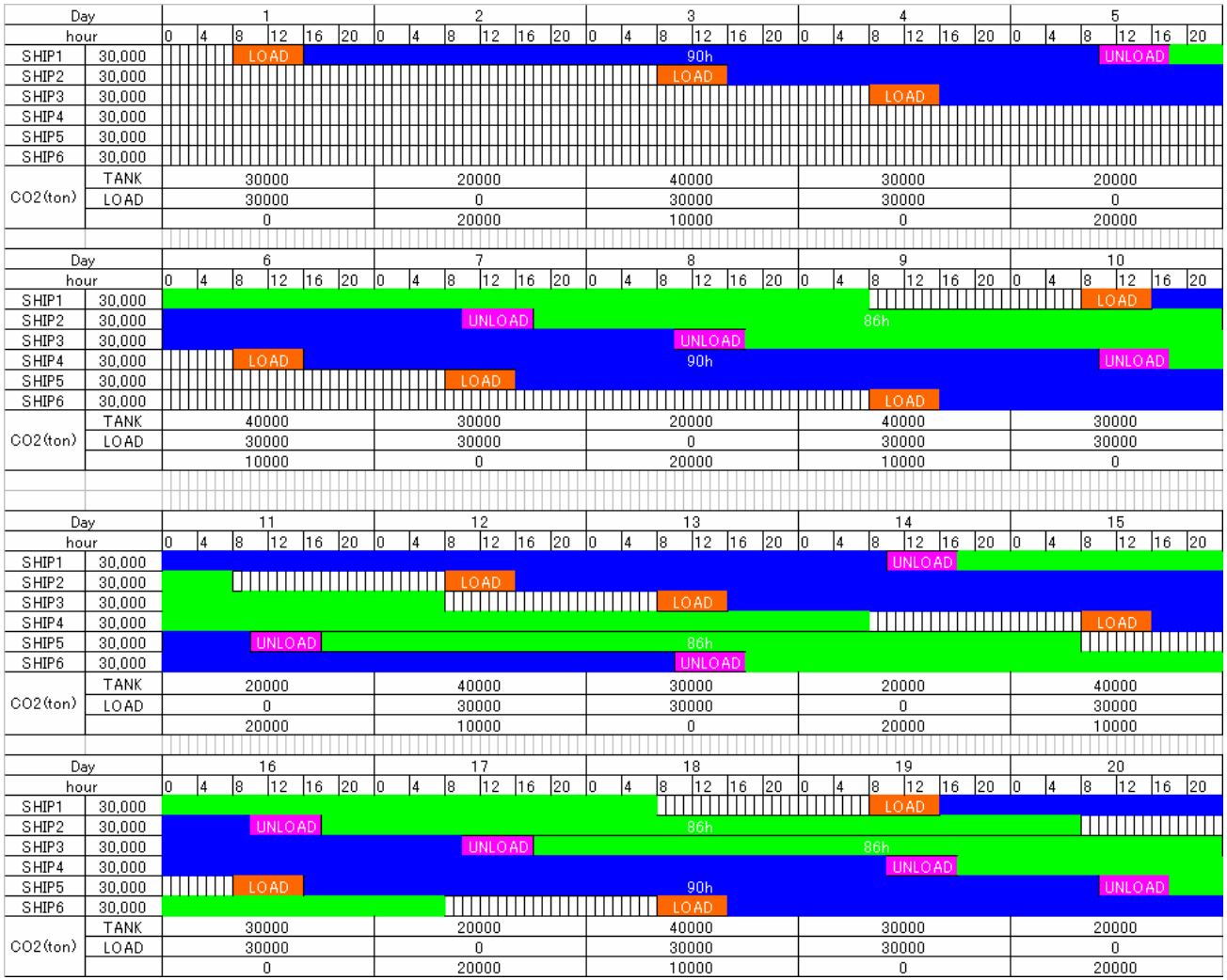
Schedule of Ship transportation ; 3000km 10000tonne 15/16kn



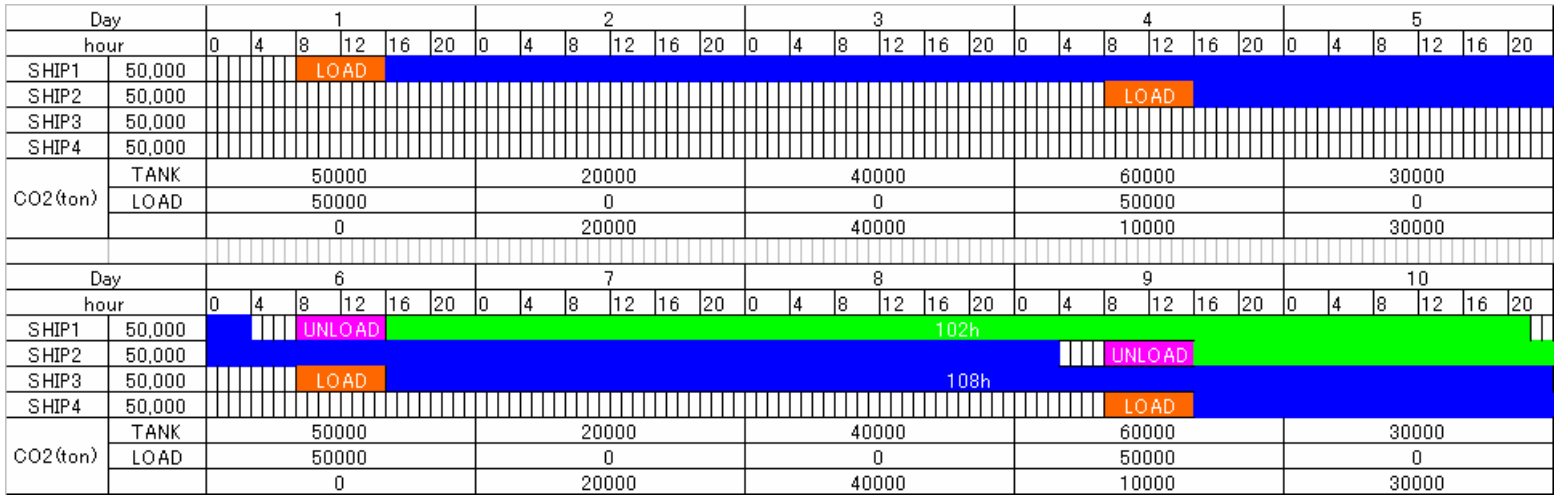
Schedule of Ship transportation ; 3000km 10000tonne 18/19kn



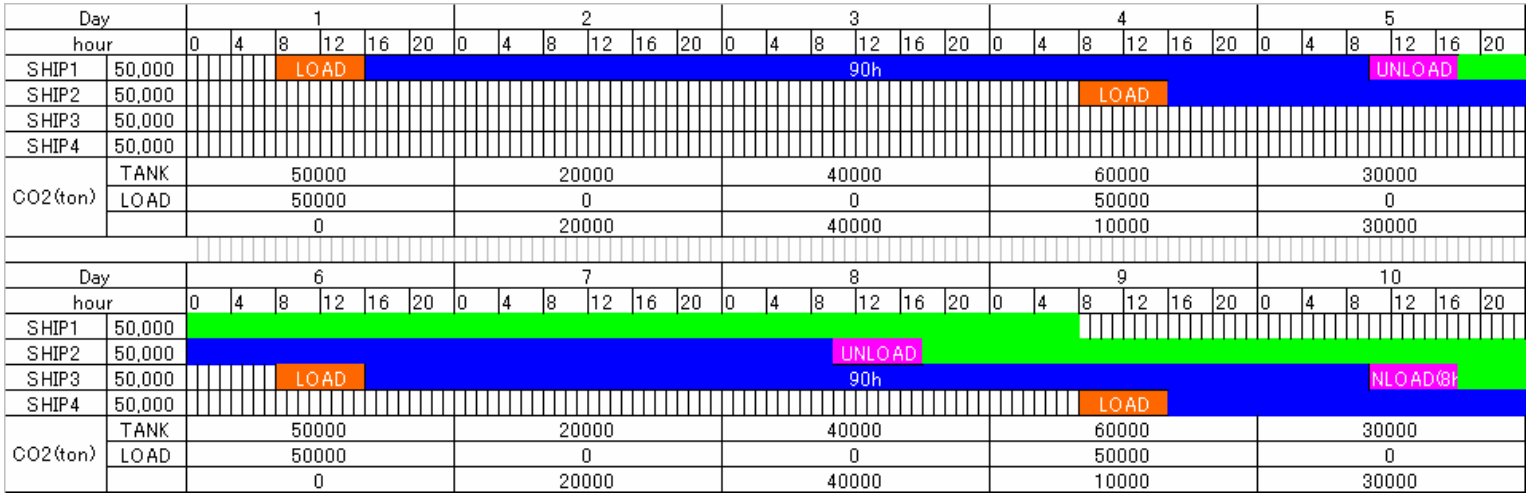
Schedule of Ship transportation ; 3000km 30000tonne 15/16kn



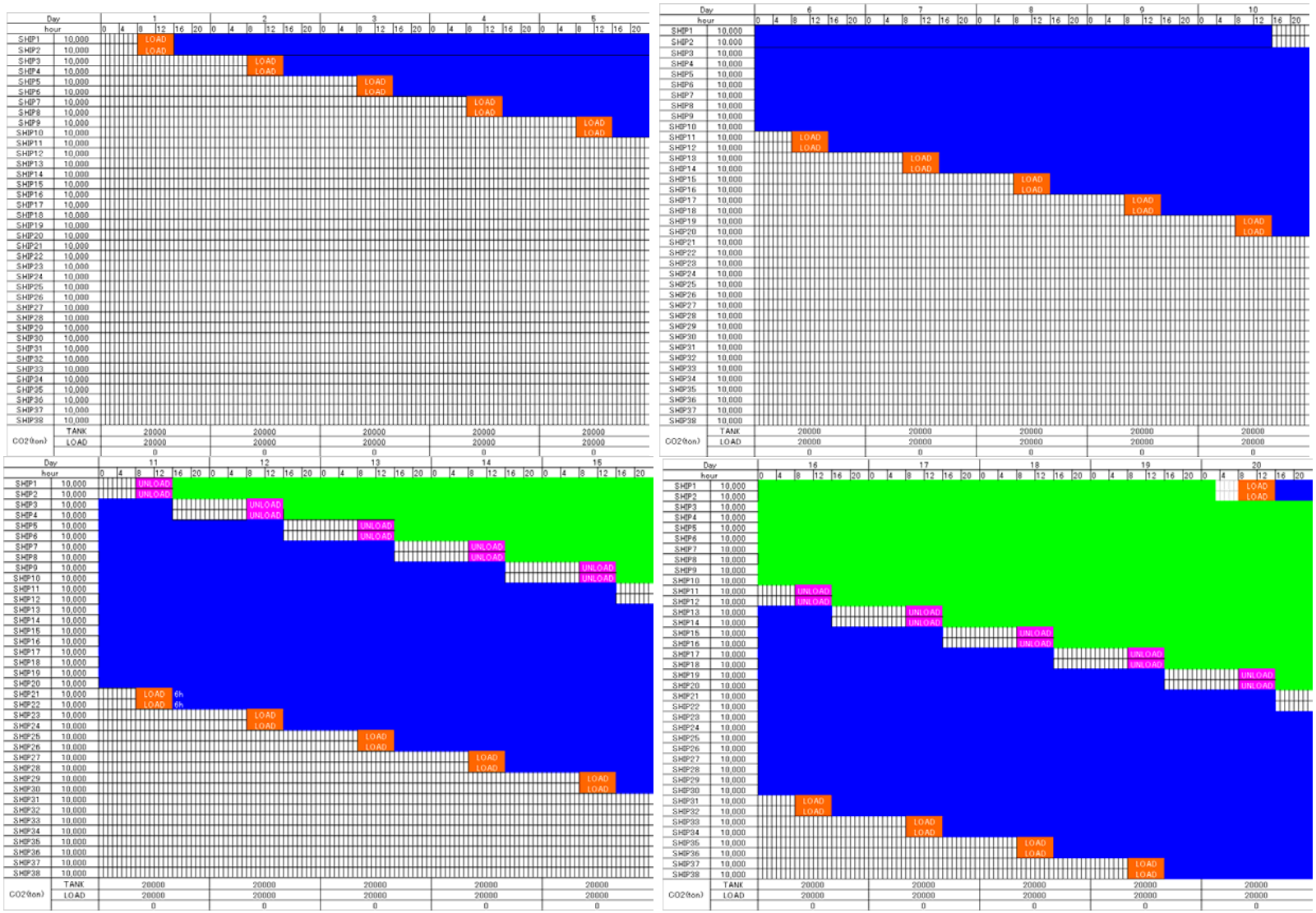
Schedule of Ship transportation ; 3000km 30000tonne 18/19kn



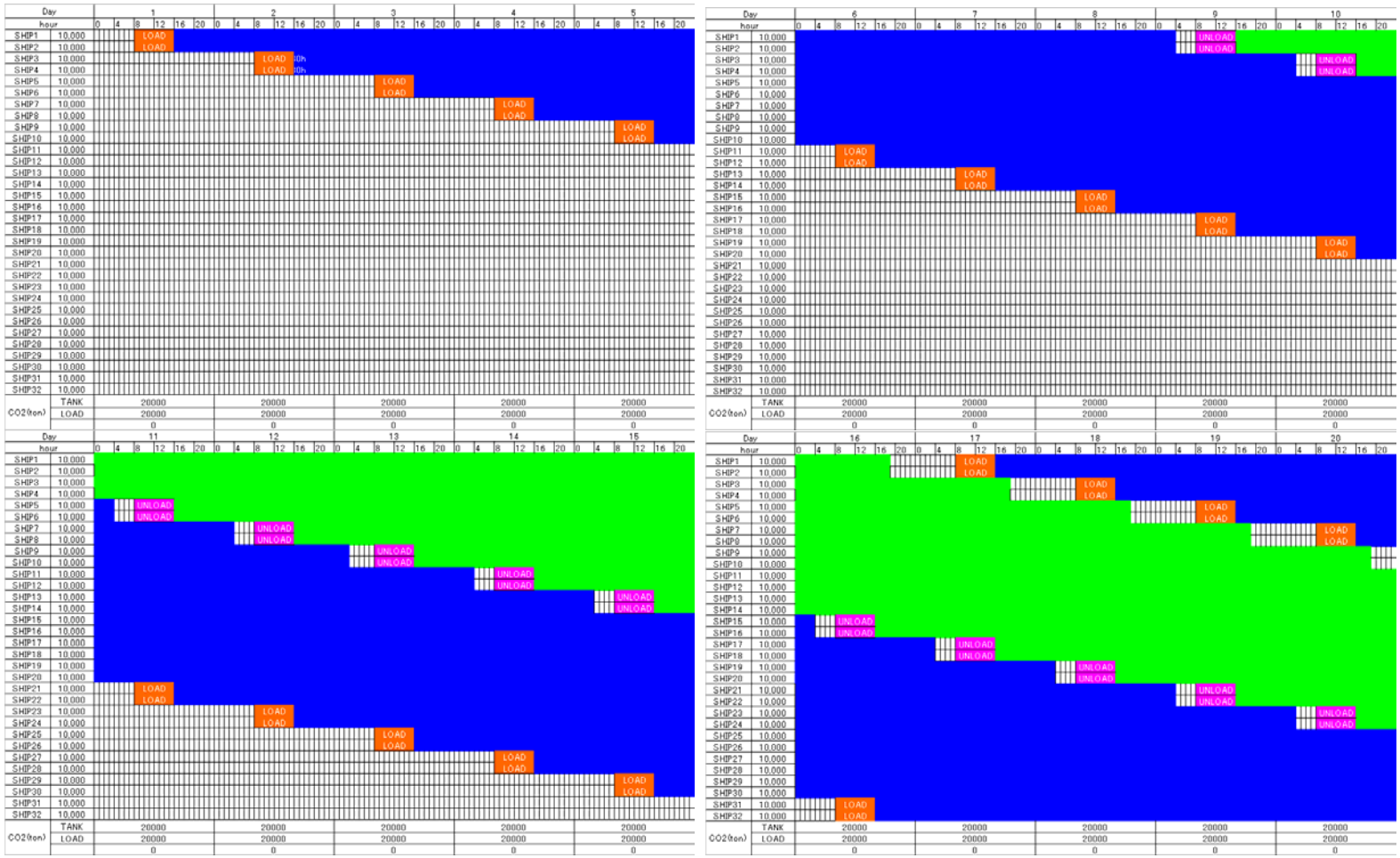
Schedule of Ship transportation ; 3000km 50000tonne 15/16kn



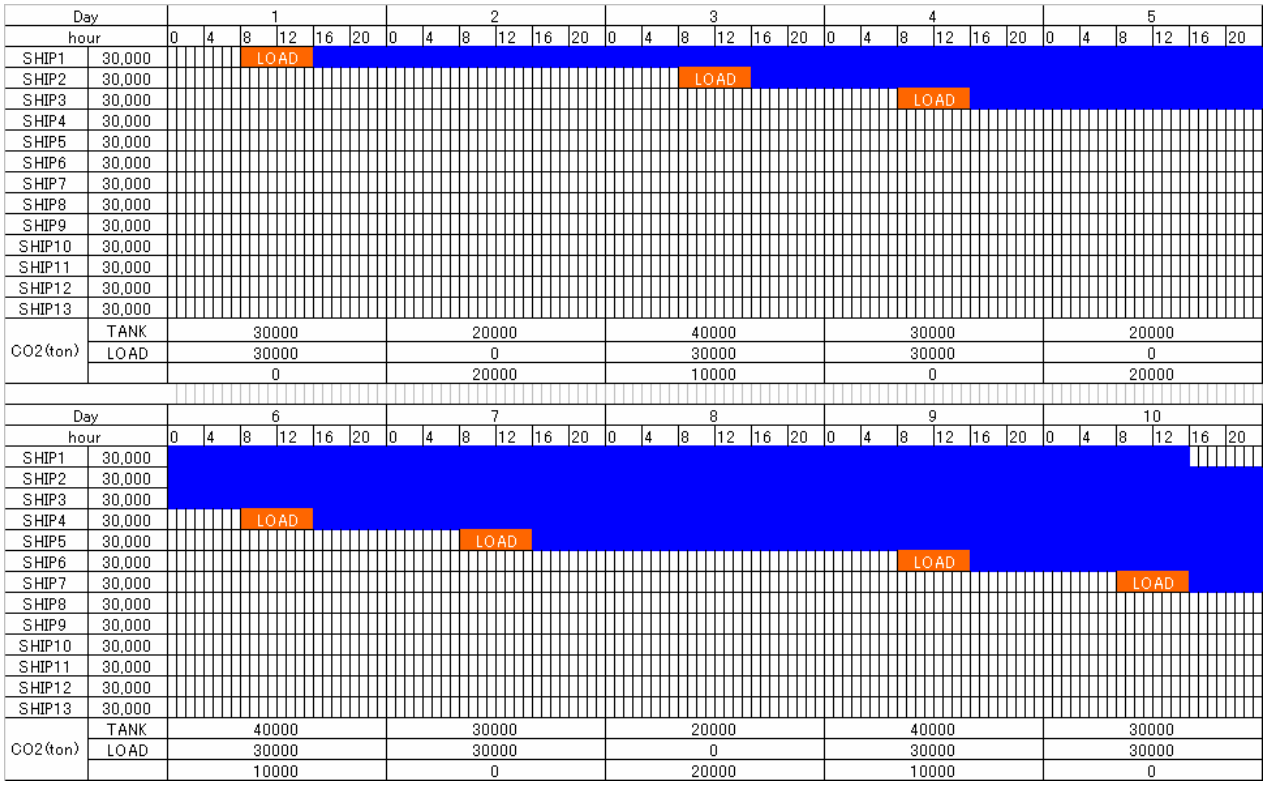
Schedule of Ship transportation ; 3000km 50000tonne 18/19kn

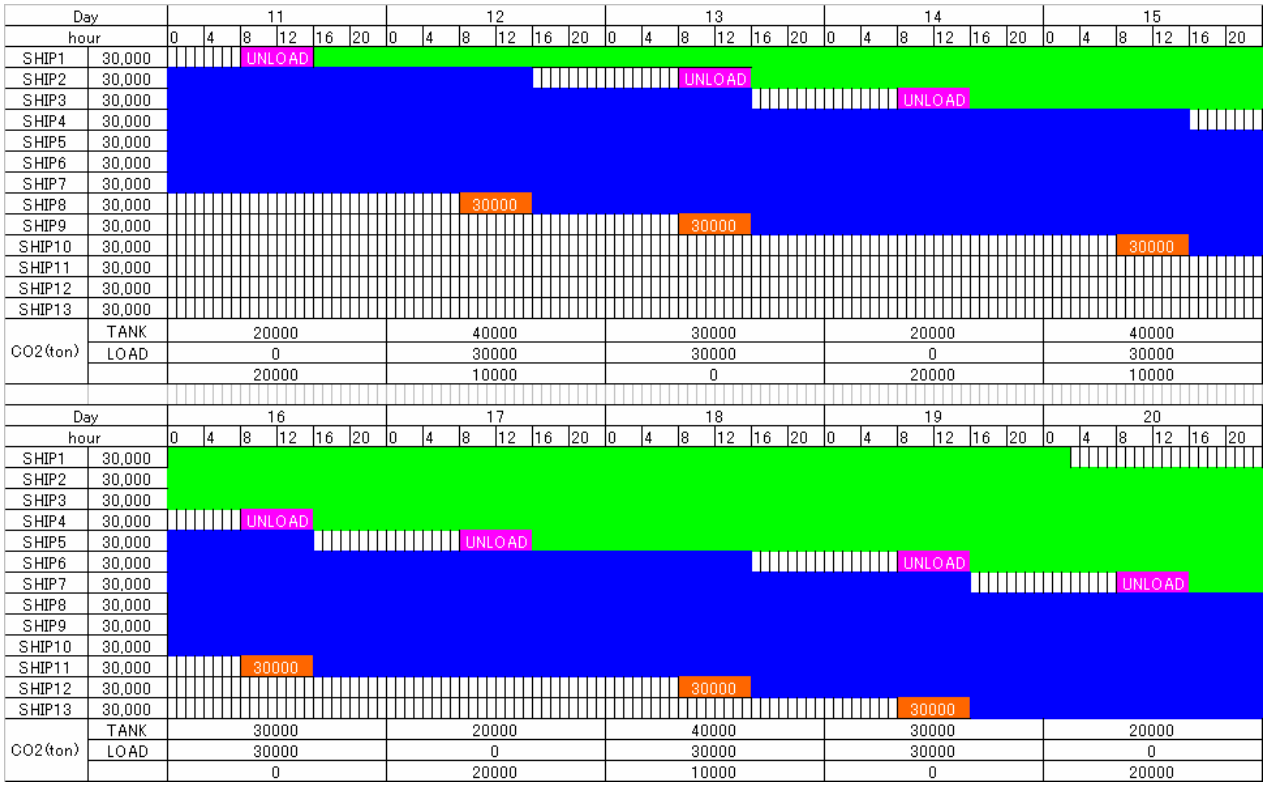


Schedule of Ship transportation ; 6000km 10000tonne 15/16kn

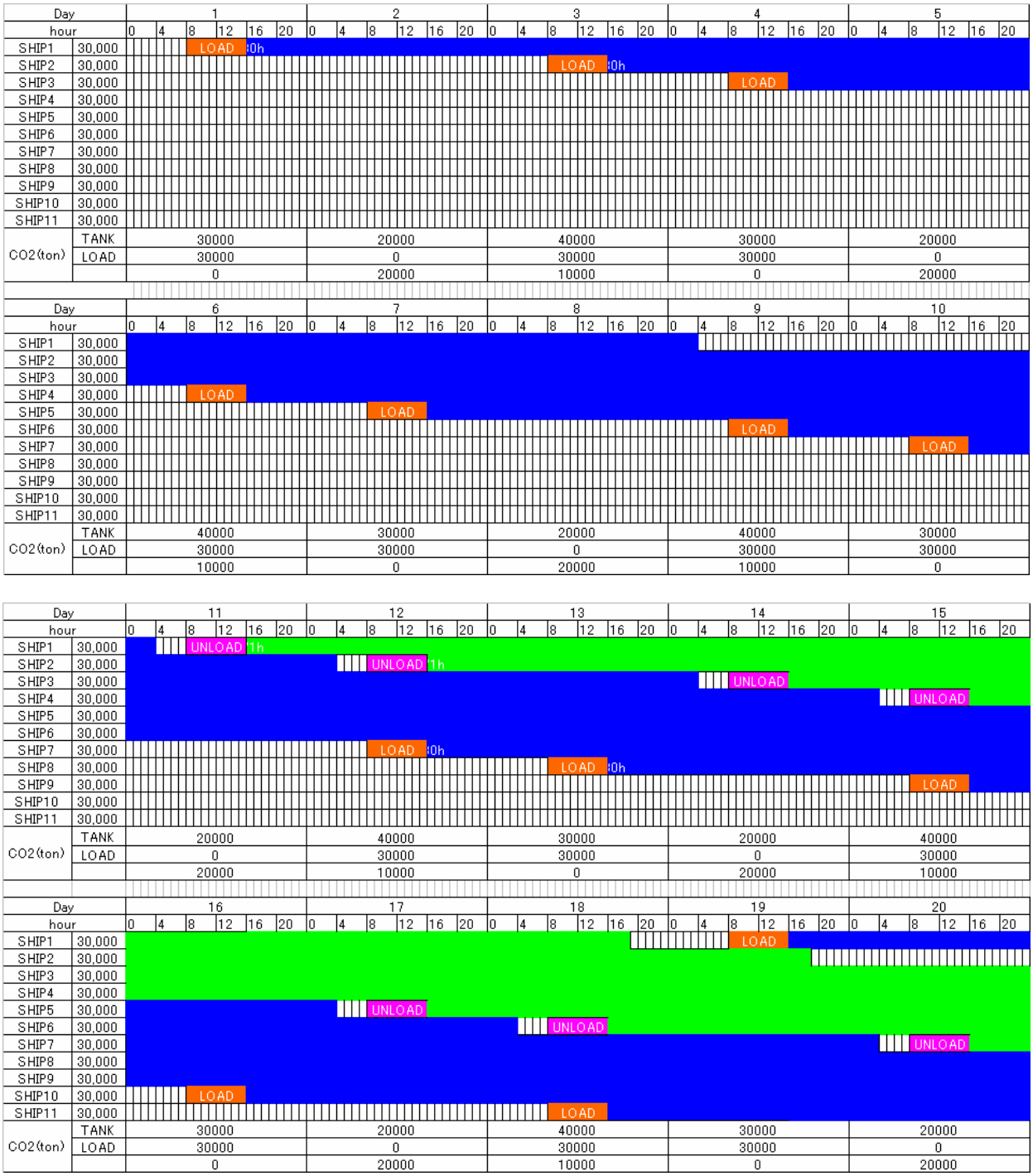


Schedule of Ship transportation ; 6000km 10000tonne 18/19kn

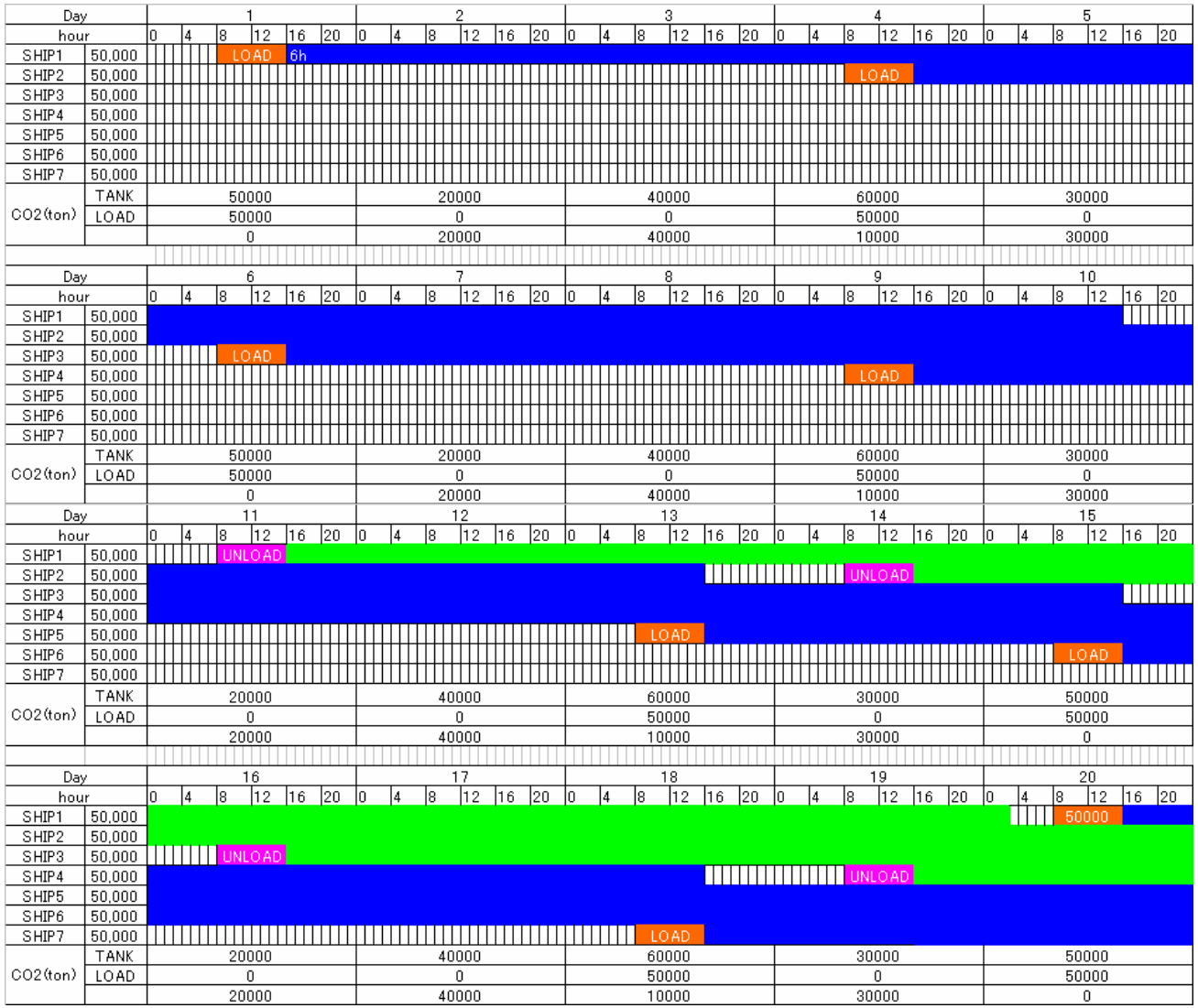




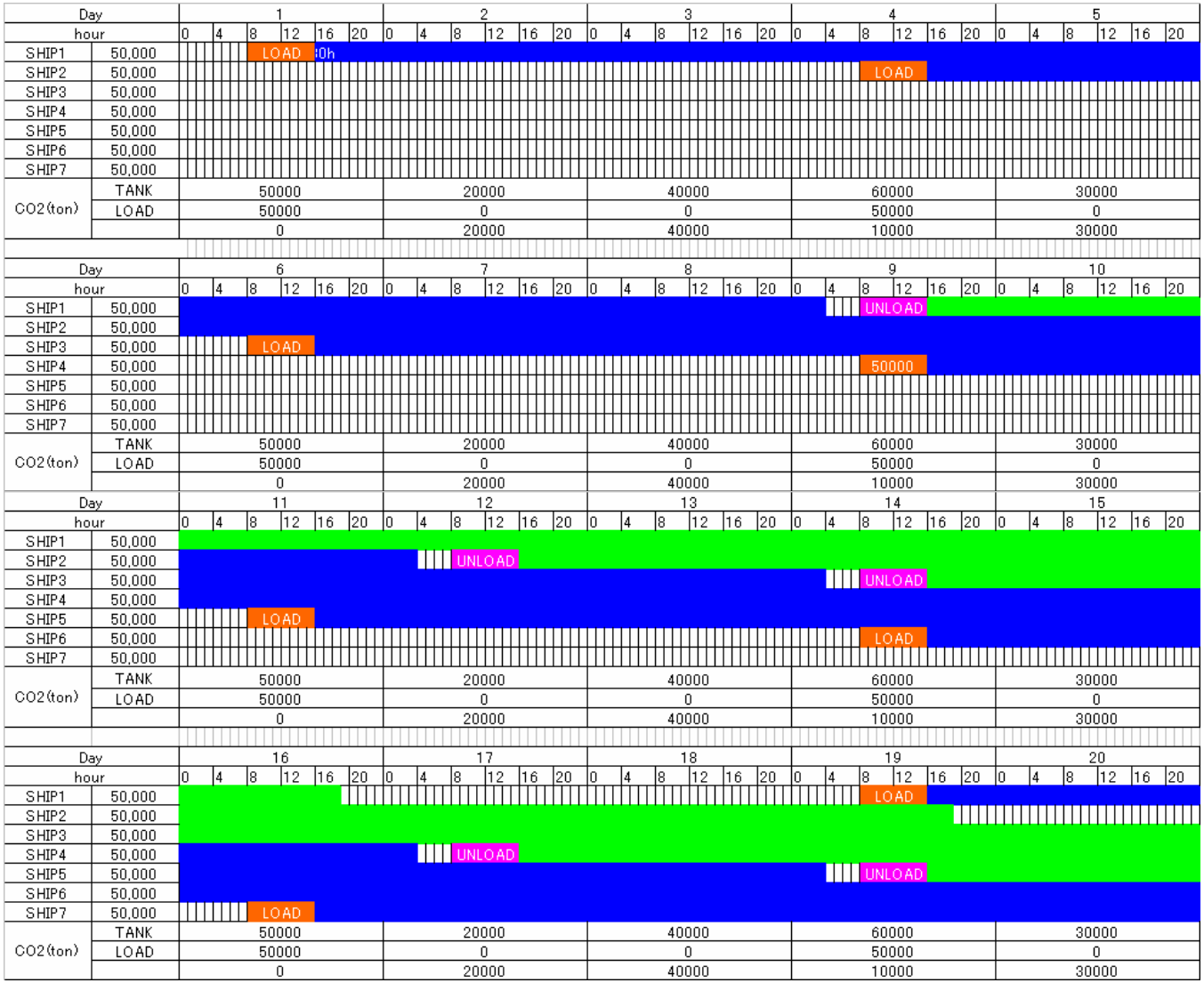
Schedule of Ship transportation ; 6000km 30000tonne 15/16kn



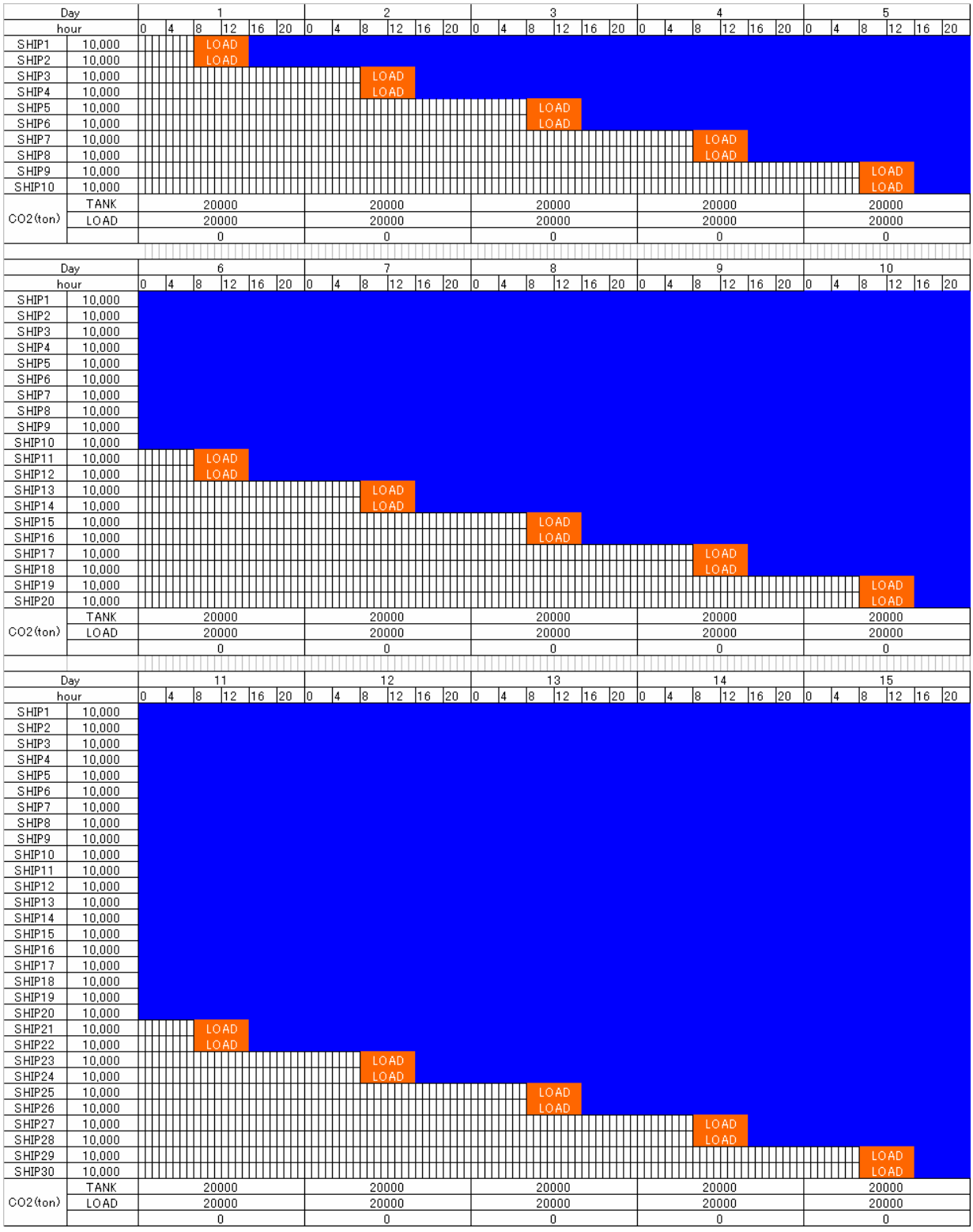
Schedule of Ship transportation ; 6000km 30000tonne 18/19kn



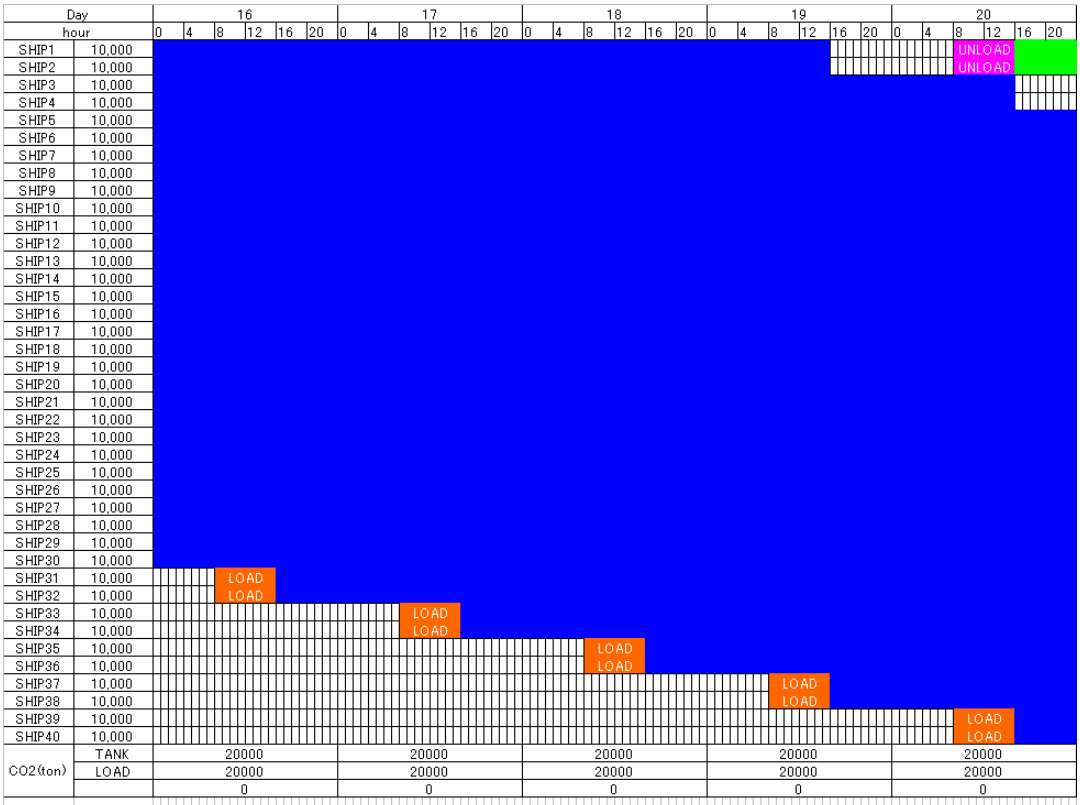
Schedule of Ship transportation ; 6000km 50000tonne 15/16kn

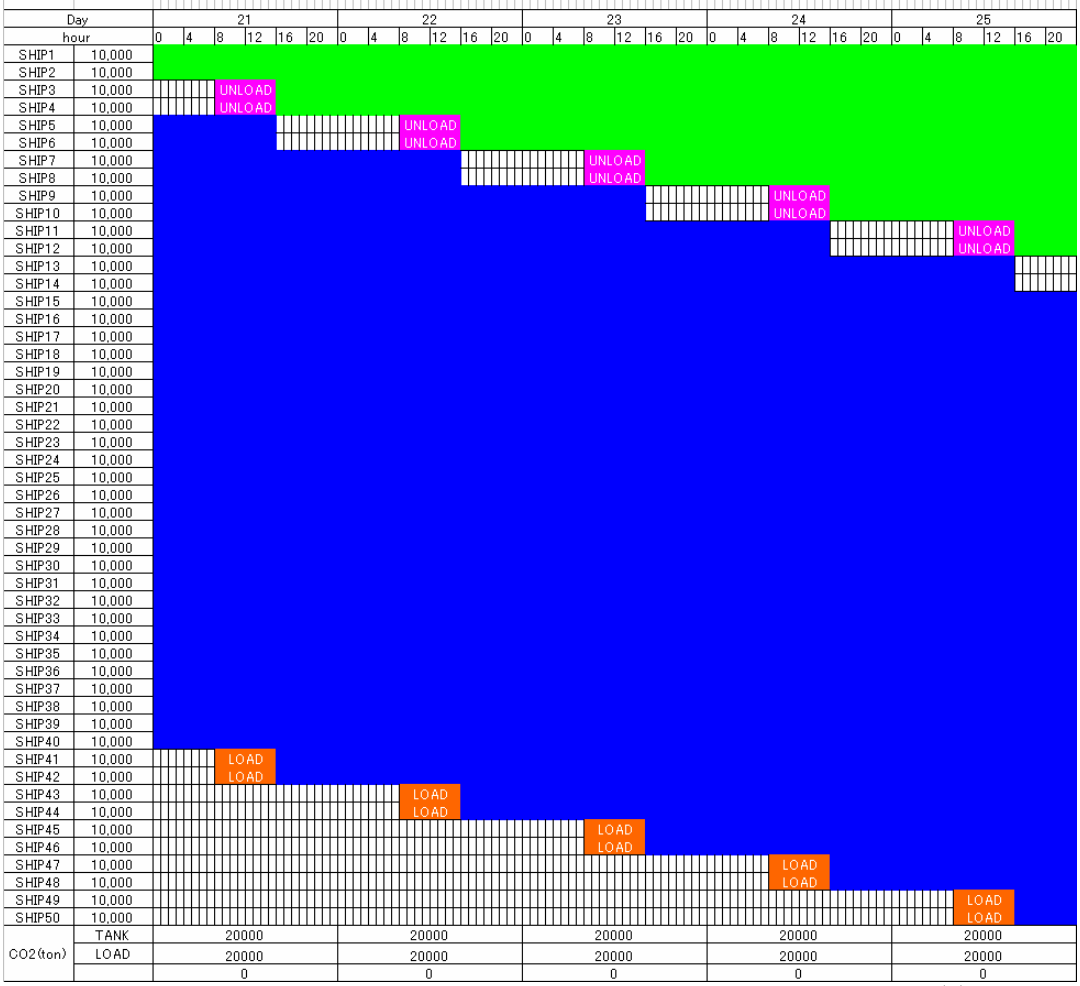


Schedule of Ship transportation ; 6000km 50000tonne 18/19kn

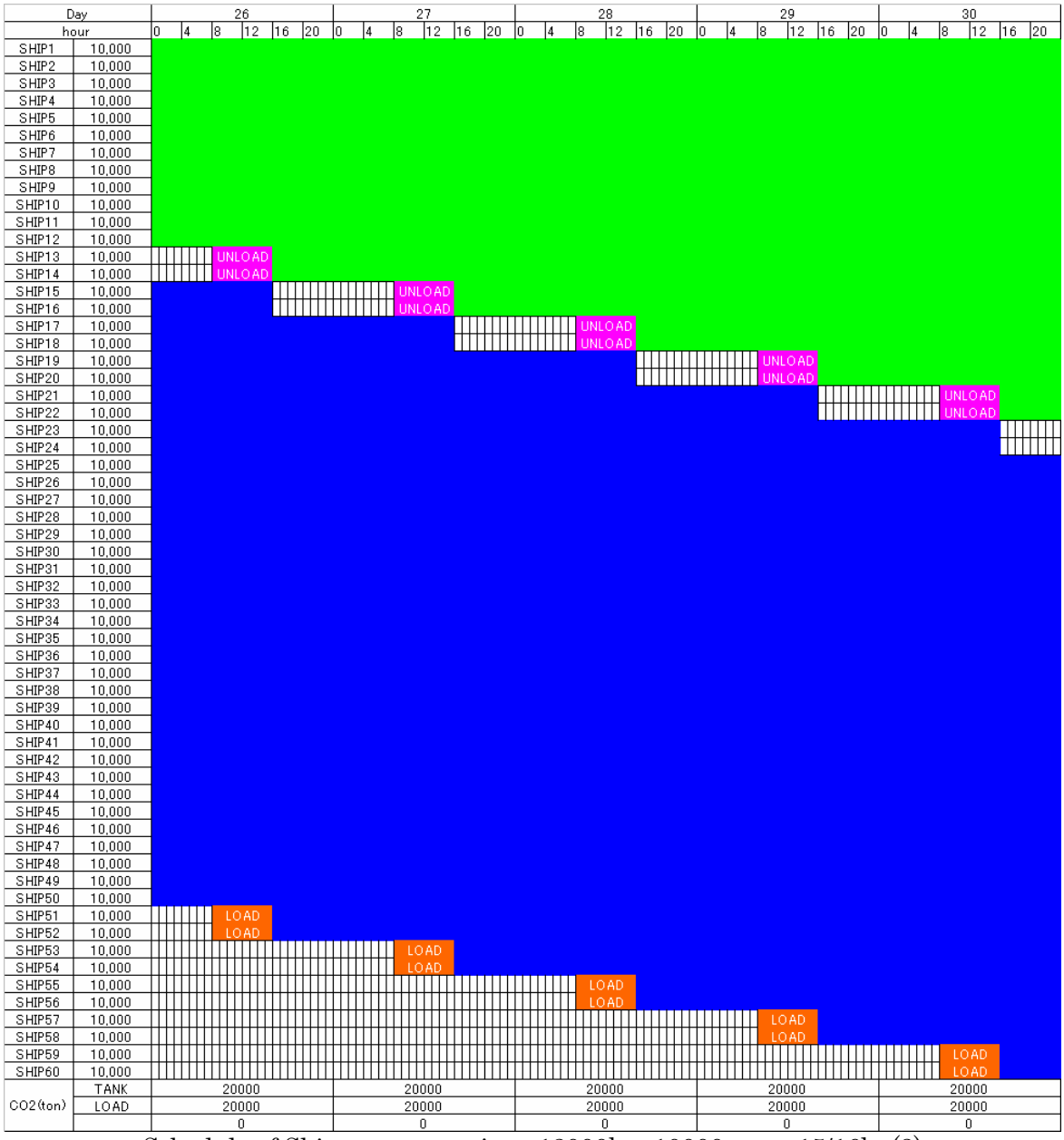


Schedule of Ship transportation ; 12000km 10000tonne 15/16kn(1)

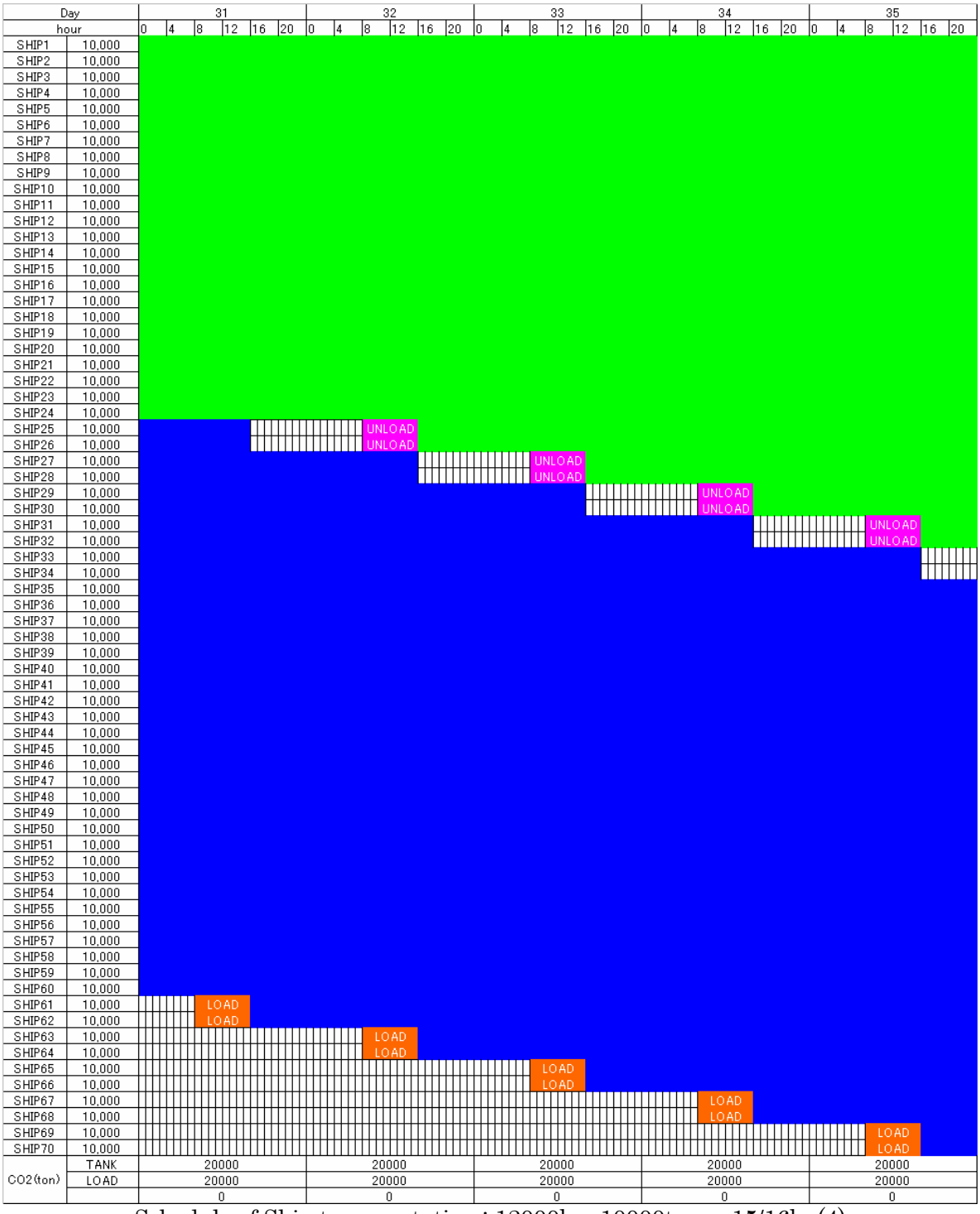




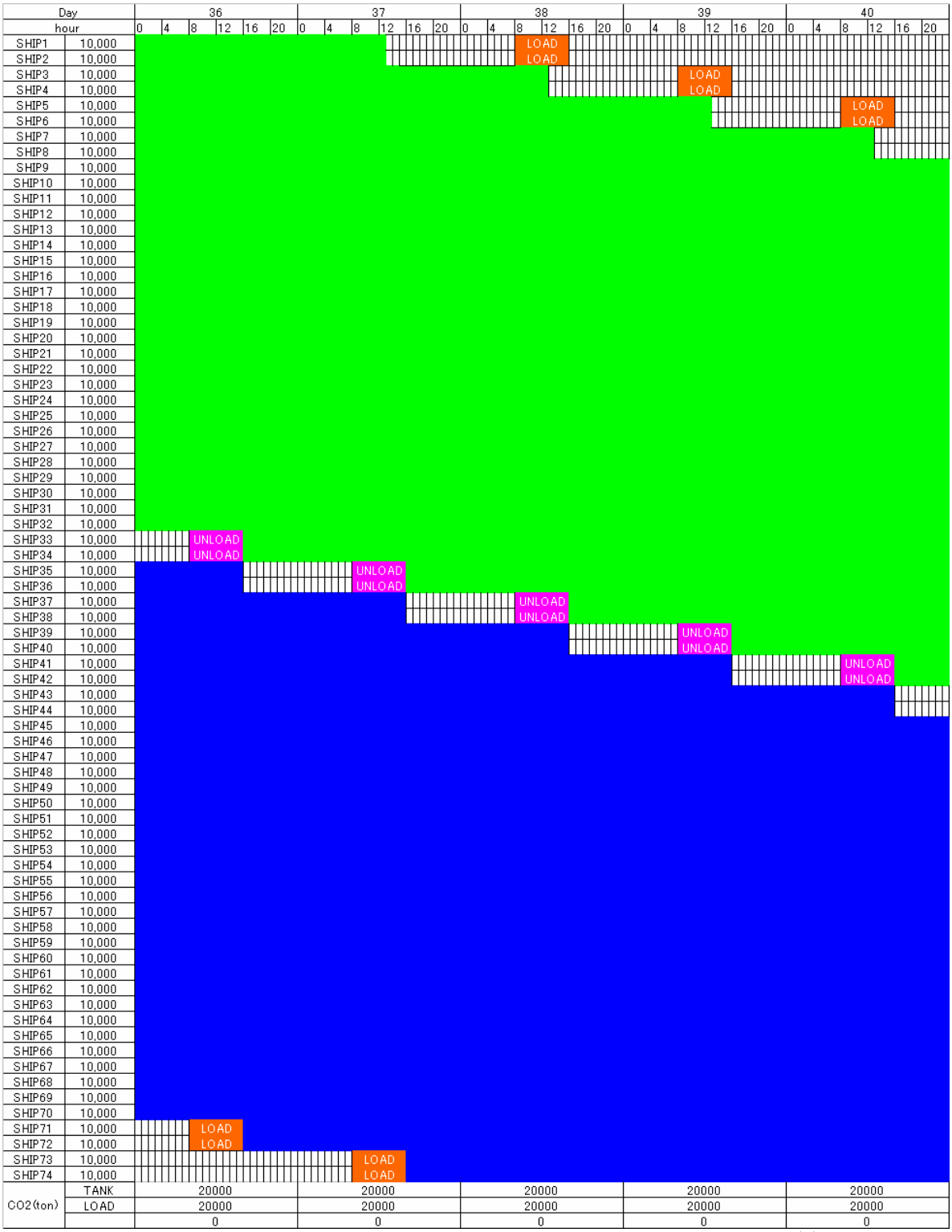
Schedule of Ship transportation ; 12000km 10000tonne 15/16kn(2)



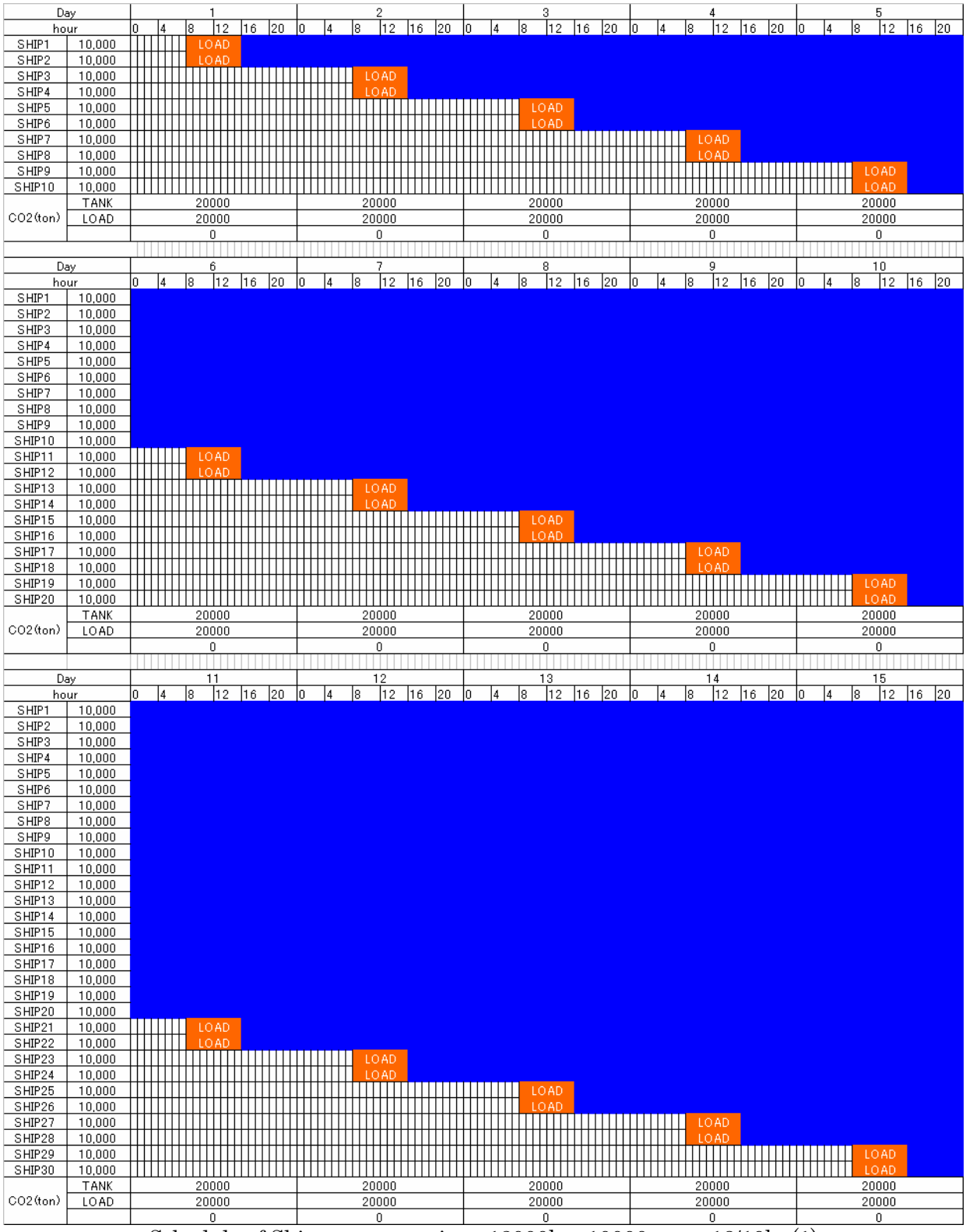
Schedule of Ship transportation ; 12000km 10000tonne 15/16kn(3)



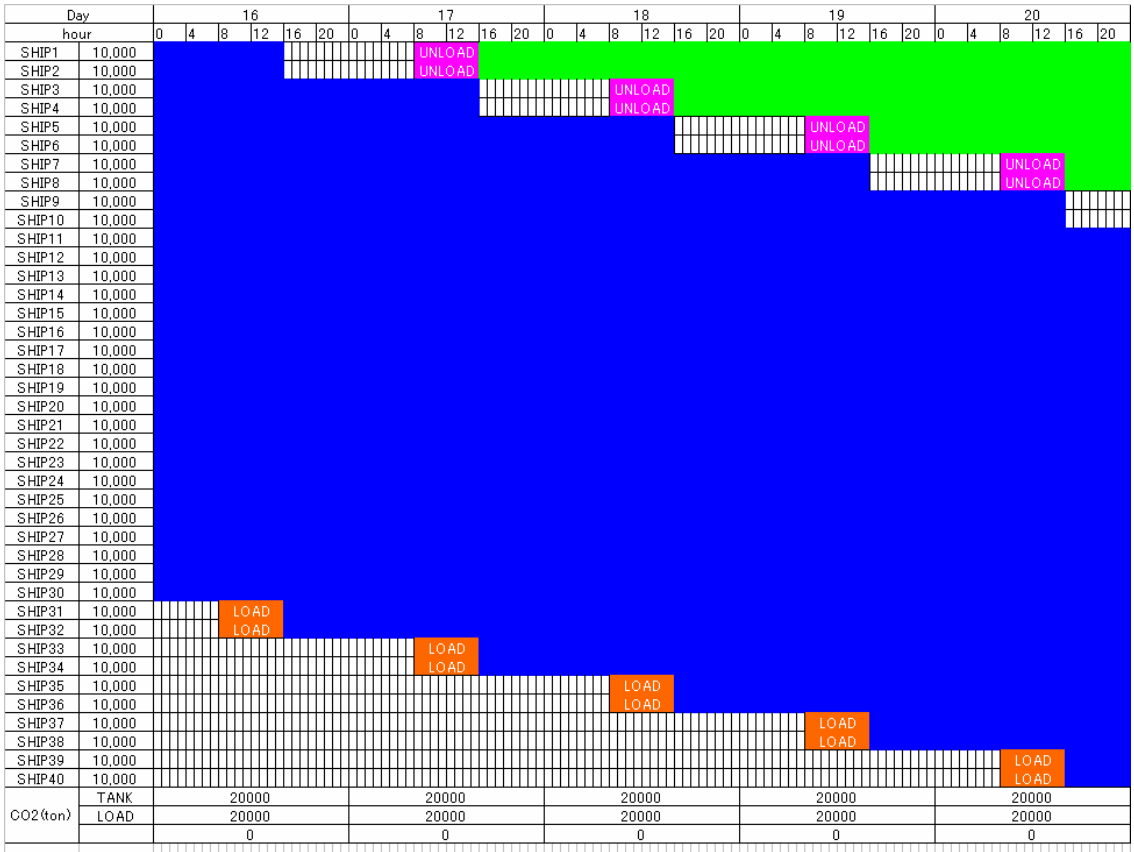
Schedule of Ship transportation ; 12000km 10000tonne 15/16kn(4)



Schedule of Ship transportation ; 12000km 10000tonne 15/16kn(5)



Schedule of Ship transportation ; 12000km 10000tonne 18/19kn(1)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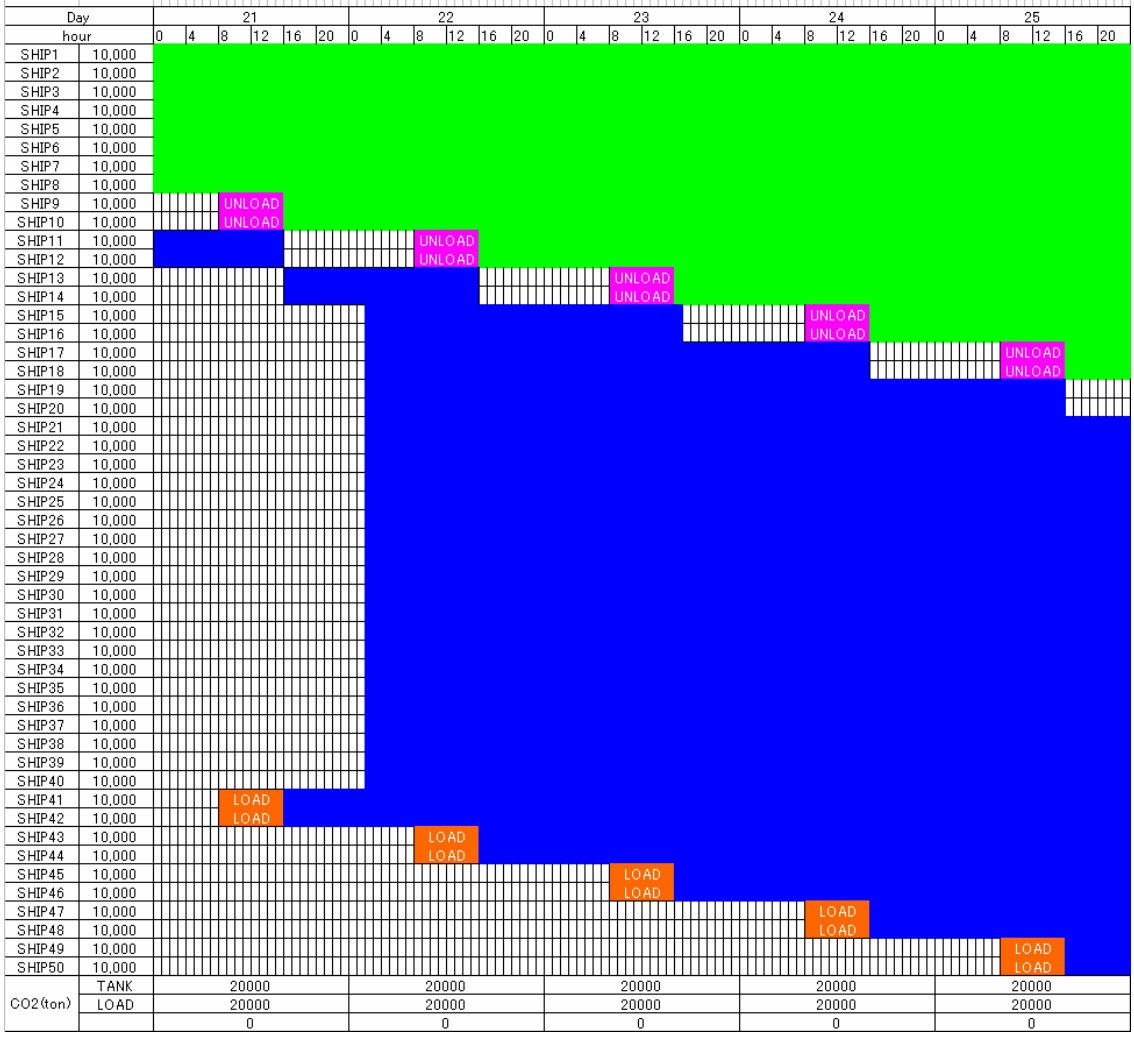
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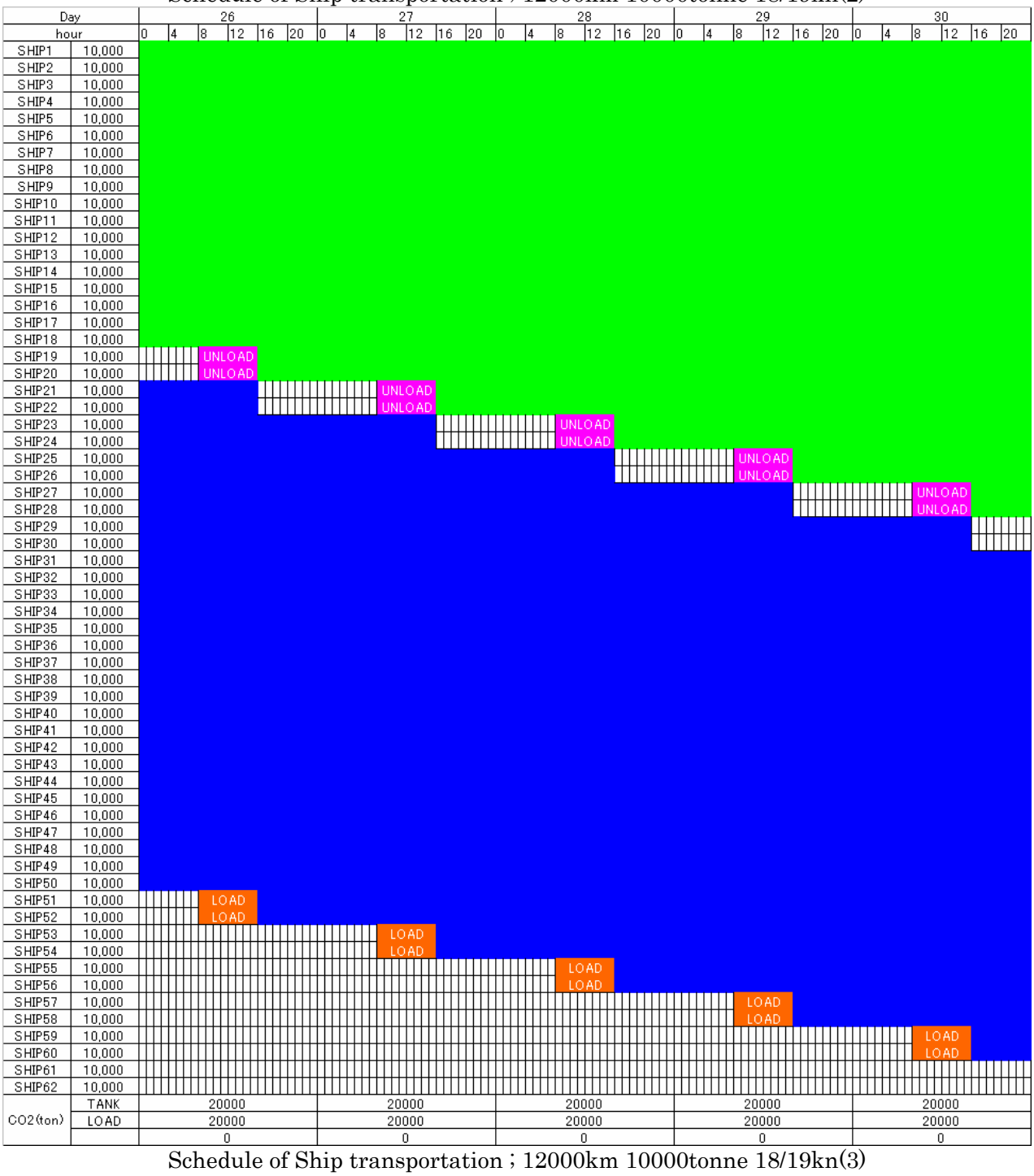
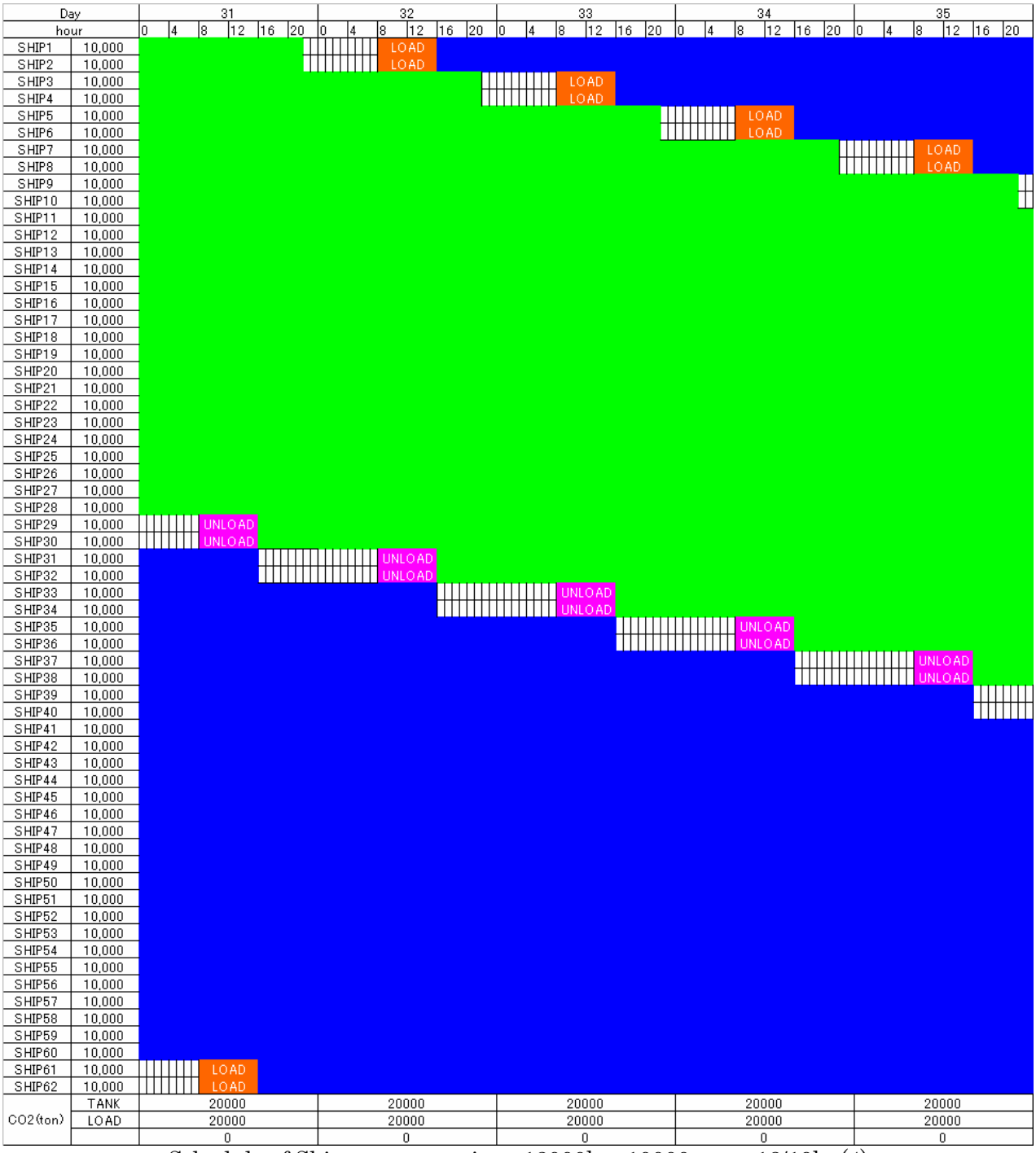
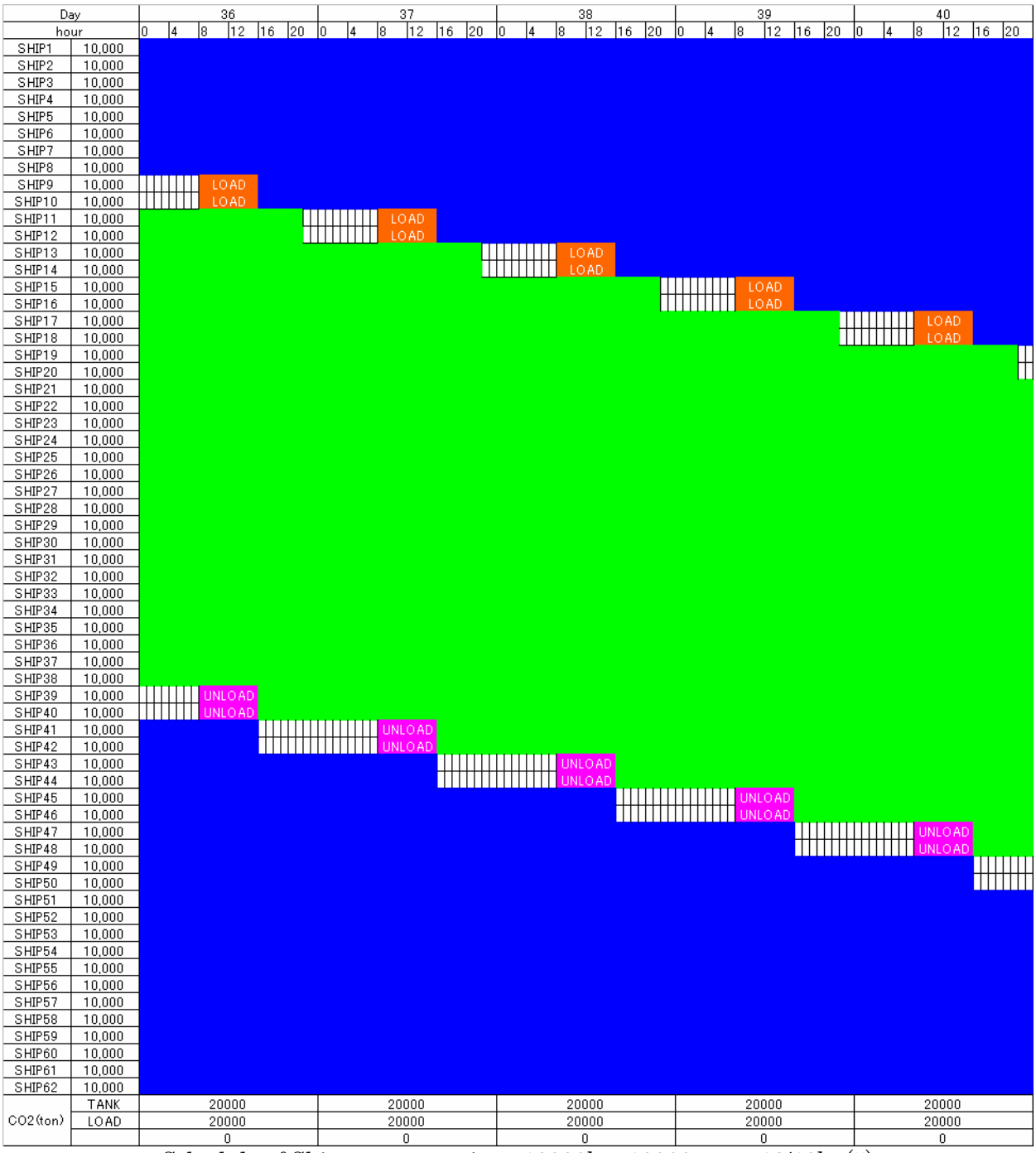
Schedule of Ship transportation ; 12000km 10000tonne 18/19kn(2)



Schedule of Ship transportation ; 12000km 10000tonne 18/19kn(3)



Schedule of Ship transportation ; 12000km 10000tonne 18/19kn(4)



Schedule of Ship transportation ; 12000km 10000tonne 18/19kn(5)

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	LOAD	0						30000						30000						0						30000					
		20000						10000						0						20000						10000					

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Day		21						22						23						24						25					
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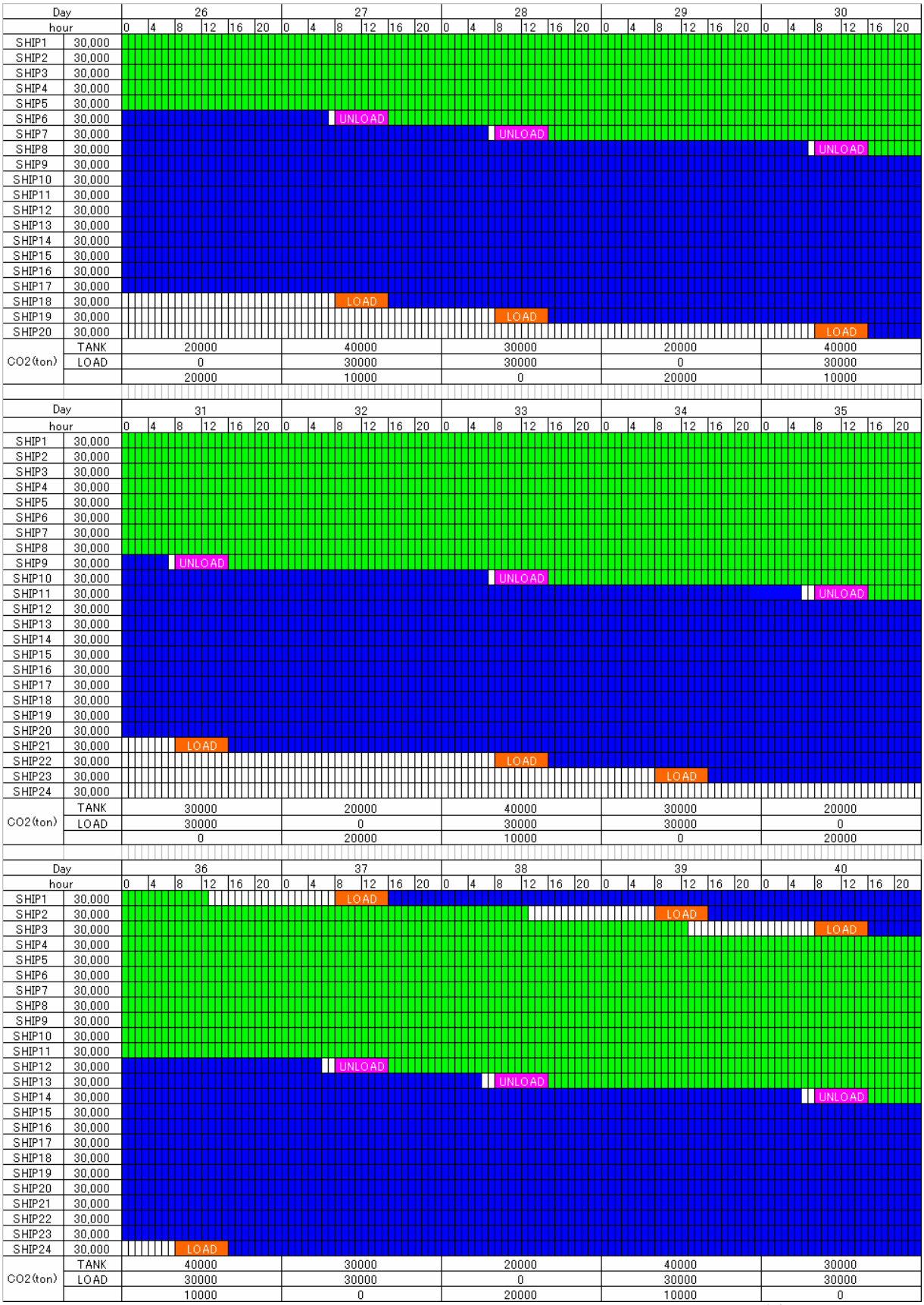
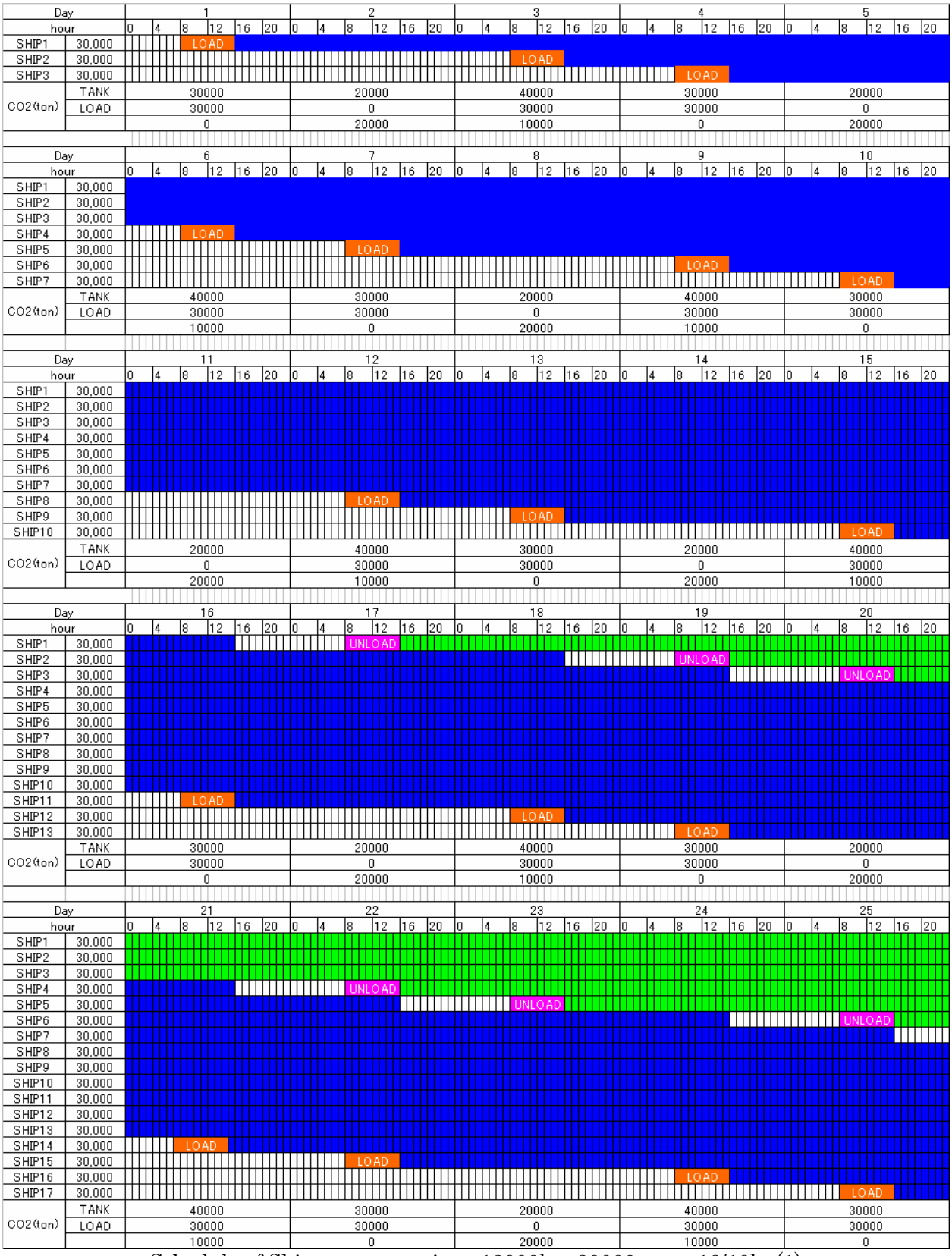
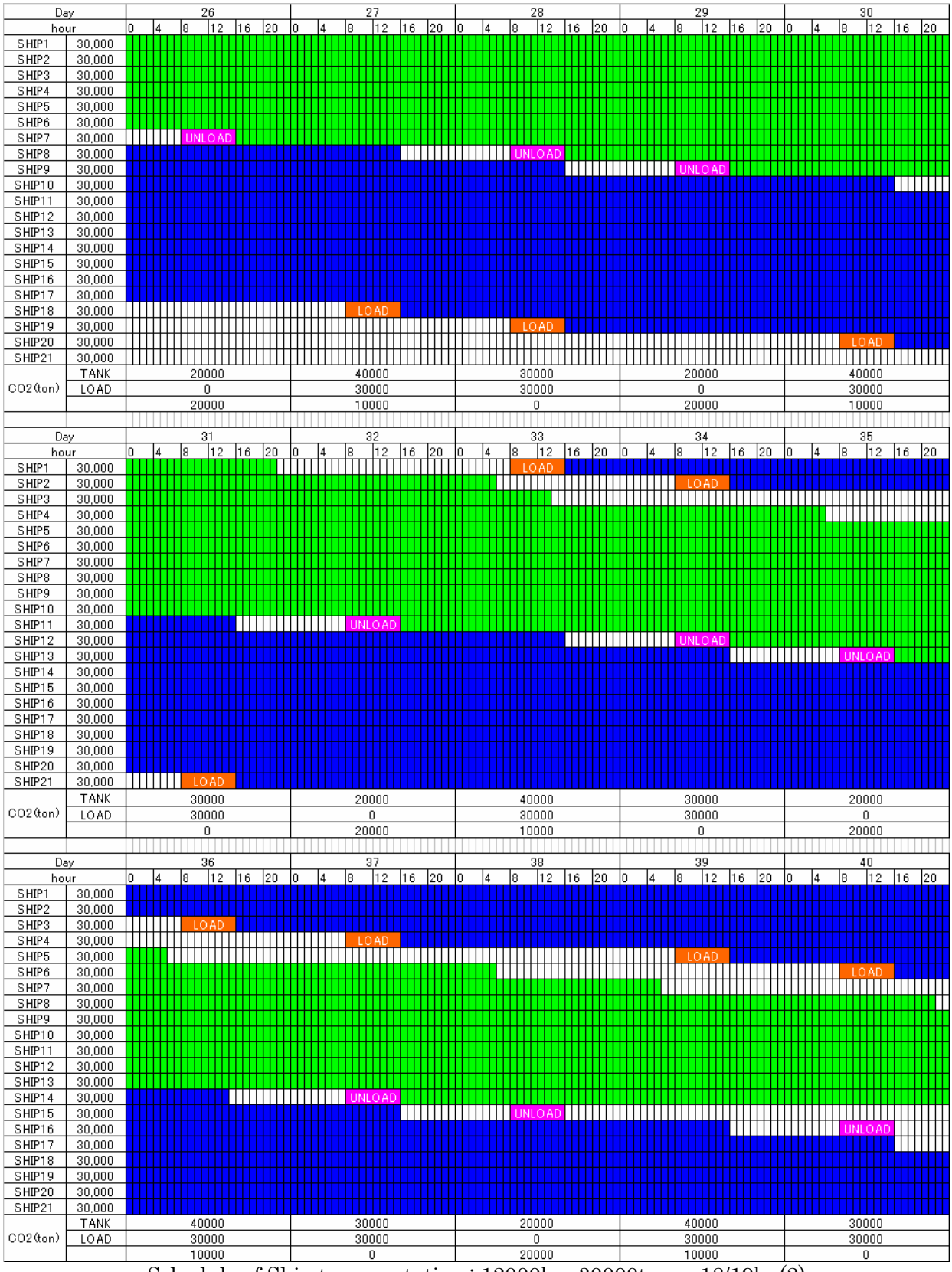
Schedule of Ship transportation ; 12000km 30000tonne 15/16kn(1)



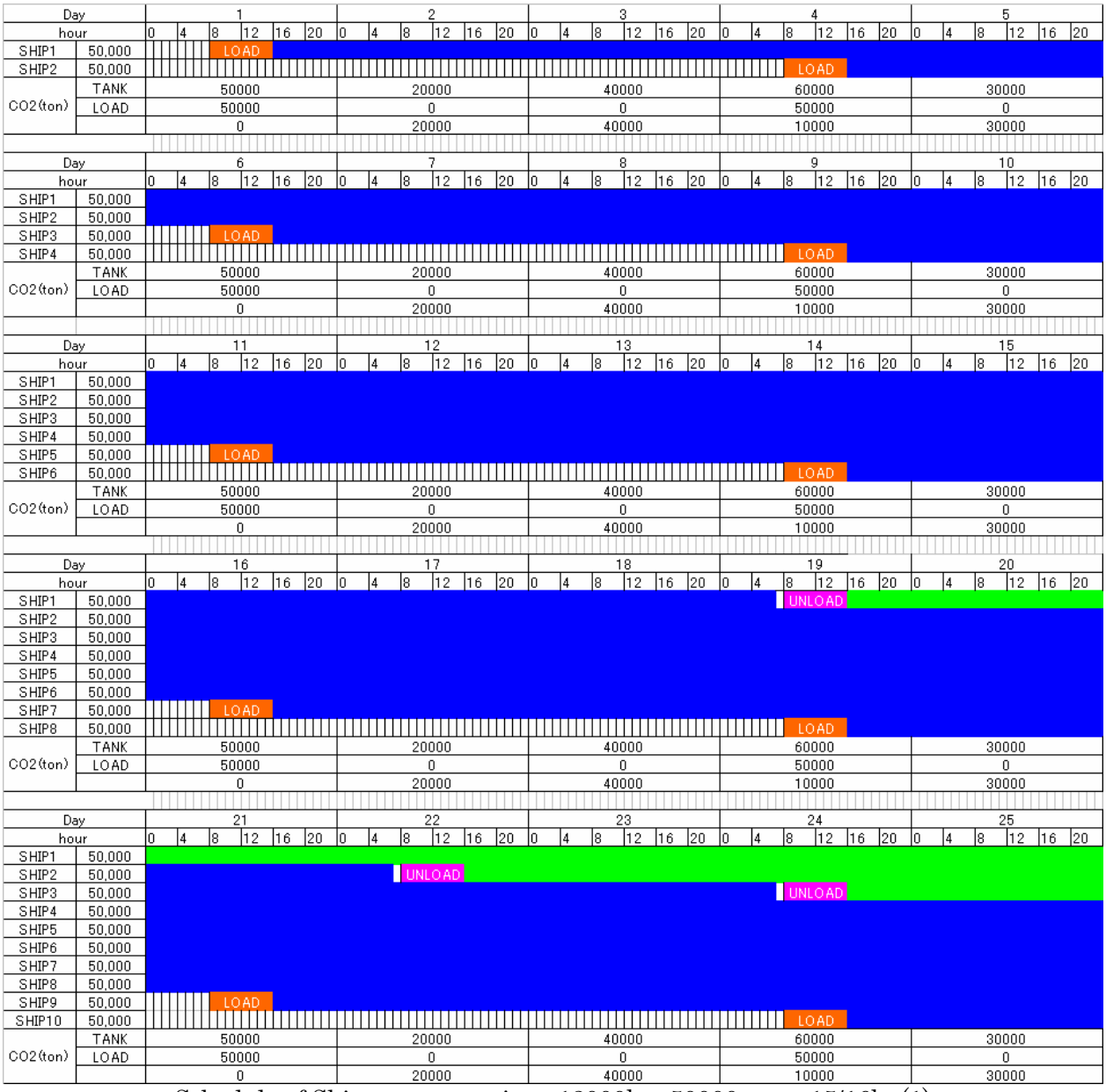
Schedule of Ship transportation ; 12000km 30000tonne 15/16kn(2)



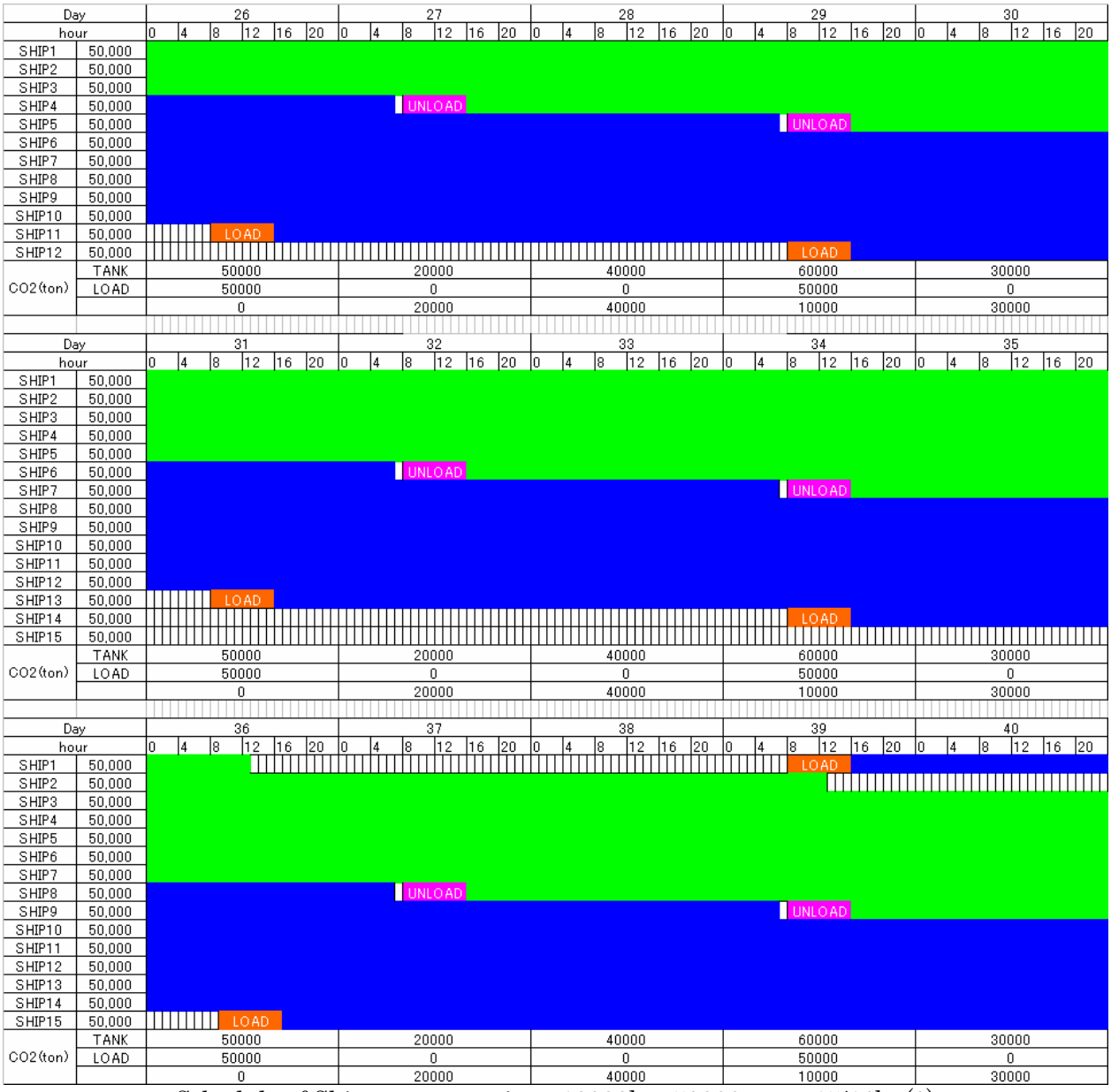
Schedule of Ship transportation ; 12000km 30000tonne 18/19kn(1)



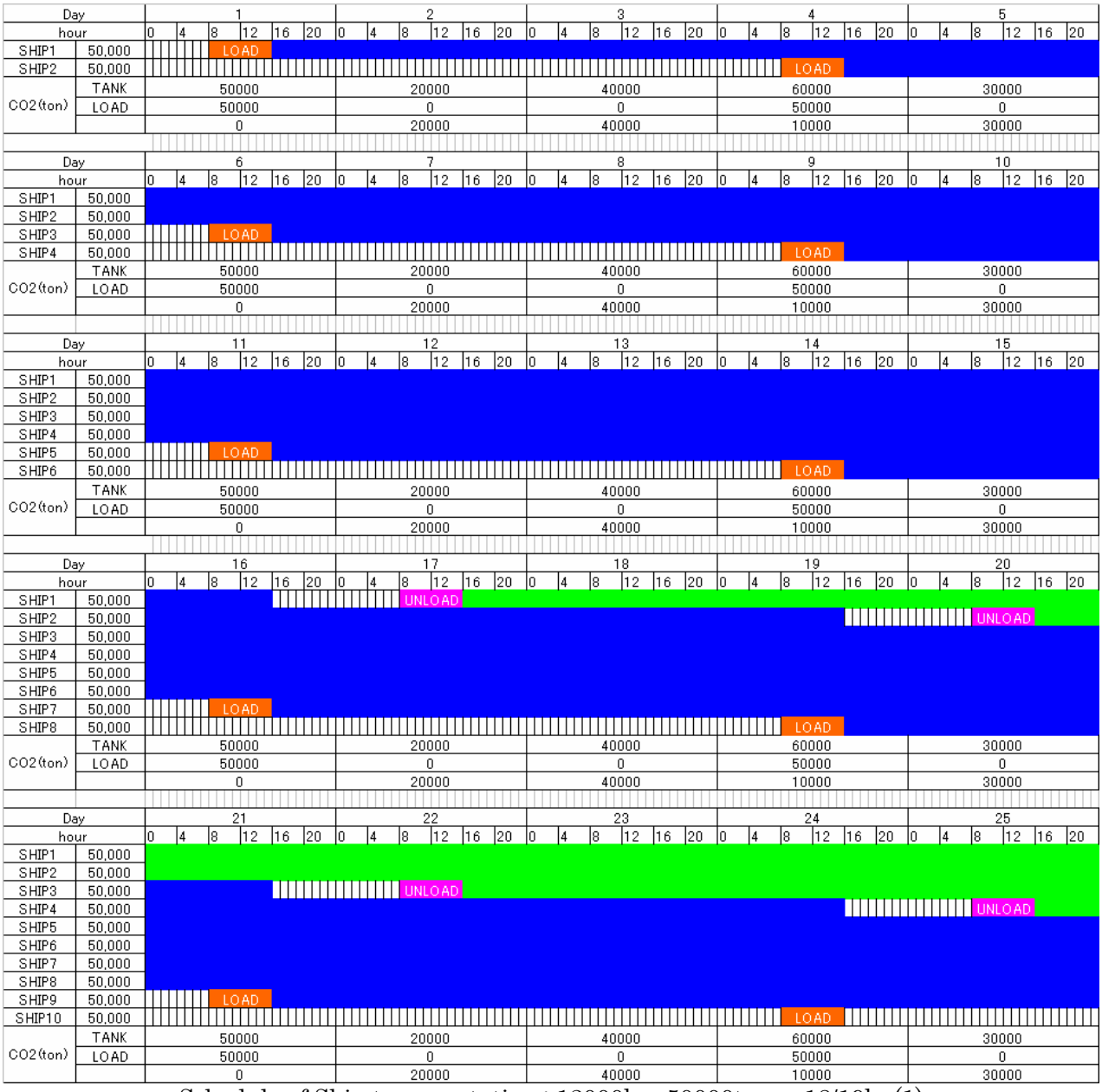
Schedule of Ship transportation ; 12000km 30000tonne 18/19kn(2)



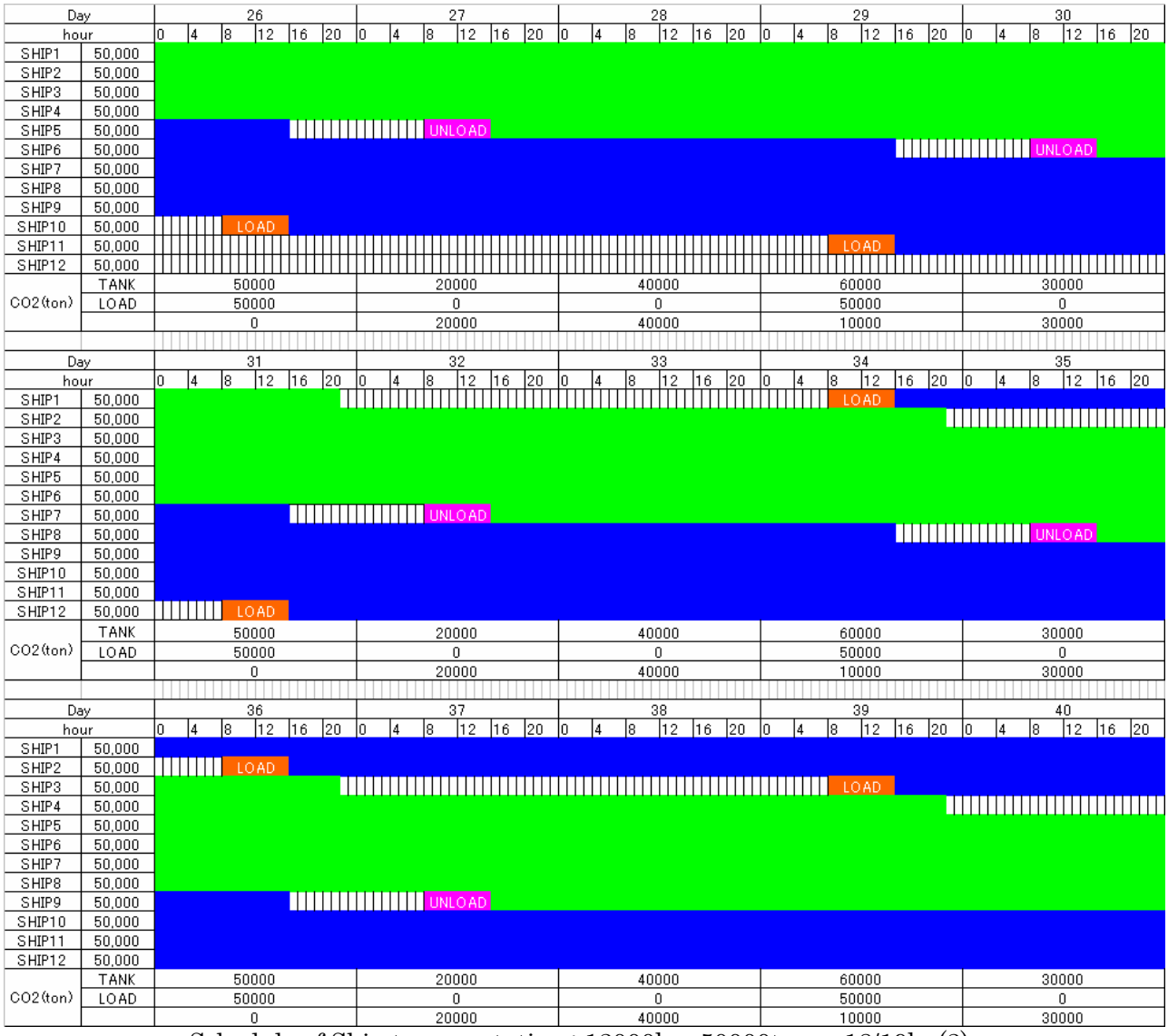
Schedule of Ship transportation ; 12000km 50000tonne 15/16kn(1)



Schedule of Ship transportation ; 12000km 50000tonne 15/16kn(2)



Schedule of Ship transportation ; 12000km 50000tonne 18/19kn(1)



Schedule of Ship transportation ; 12000km 50000tonne 18/19kn(2)