CCDoTT

Center for the Commercial Deployment
of Transportation Technologies

ALTERNATIVE POWERING FOR MERCHANT SHIPS

Task 3 – Economic Analysis of Powering Alternatives

Submitted by:

Chris B. McKesson, PE, Task Manager
Program Element 724110 Fiscal Year 2000

Submitted to:

Center for the Commercial Deployment of Transportation Technologies
California State University, Long Beach Foundation
6300 State University Drive, Suite 332 · Long Beach, CA 90815 · 562.985.7394

This program has been funded by the Center for Commercial Deployment of Transportation Technologies (CCDoTT) at California State University, Long Beach. Distribution authorized only to U.S. Government agencies to protect information not owned by the U.S. Government and protected by a Recipient confidentiality statement, or received with the understanding that it not be routinely transmitted outside the U.S. Government. Any requests for this document shall be referred to the Maritime Administration Office of Acquisition, which will review such requests in coordination with the Office of the Chief Counsel and the Recipient.

16 November, 2001

CONTENTS

TABLES

FIGURES

ALTERNATIVE POWERING FOR MERCHANT SHIPS

Task 3 – Economic Analysis of Powering Alternatives

EXECUTIVE SUMMARY

This report documents a project to study the economic merit of alternative powering systems for container ships. The concept of the project is to assess whether there is economic incentive to develop alternative powering systems for container ships: Would such systems result in improved shipping economies?

The first report in this project described the state of the art of container ships and shipping routes. This third report completes the series by presenting an economic assessment of the impact of each of those alternative powering systems when applied to a notional baseline container ship having the following characteristics:

Capacity	6000 teu
Service Speed	25 knots
Service Range	6000 nautical miles (unrefueled)
Power Required	75 MW

The economic assessment is conducted parametrically, based on the following items:

kg / kW machinery weight
kg / kW-h fuel consumption
$ / kW acquisition cost
$ / kW-h fuel cost

Increases or decreases in weight compared to the diesel-mechanical baseline are treated as changes in the cargo capacity of the ship. Cargo capacity is also impacted by the required ship fuel. The diesel baseline ship requires some 3000t of fuel. Changes from this baseline fuel load will result in increases or decreases in available cargo capacity.

Any system which reduces the weight of the propulsion plant will result in increased cargo lift capacity and thus increased revenue. To account for this factor the weights of the alternative propulsion systems have been compared with the weights of the baseline low-speed diesel system. Firstly, the weight of the propulsion alternative is compared to the weight of the diesel baseline. Any difference in weight is allocated to the ship as cargo capacity, according to an input value of homogenous container weight. Next, an input value of slot cost for the diesel baseline ship is provided. The propulsion related costs described above are divided by the total slot-days for the ship, to arrive at a propulsion-fraction of slot cost. This fraction varies from propulsion alternative to propulsion alternative.

The non-propulsion portion of slot cost is determined by subtracting the diesel baseline propulsion cost from the input market-rate slot cost. This subtraction leaves a residual slot cost which represents all portions of the ship not included in the propulsion cost estimate.

The non-propulsion total cost is determined by multiplying the slot-days times the non-propulsion slot cost, only for the baseline diesel ship. The non-propulsion cost and the propulsion cost are summed. The result of the calculation is a net slot cost prediction for each propulsion alternative.

RESULTS: A gas turbine driven ship suffers a 30% to 120% slot-cost penalty. The economic picture of the turbine is greatly influenced by fuel cost. The gas turbine consumes more fuel than the baseline diesel, and this fuel is higher priced than that consumed by the diesel.

The nuclear-electric option is the lightest weight of all the options. As a result of the teu increase this cost increase is leveraged downward, such that the best-assumptions Nuclear slot cost is only $11.32 (as compared to the baseline diesel slot cost of $10.00). This is the lowest slot cost of any of the propulsion alternatives considered. The “worst-assumptions” version of the nuclear option results in a slot cost of $13.29, a 33% increase over the baseline.

The advantage of the fuel cell lies in its lower specific fuel consumption (SFC) compared to the diesel. The fuel cell is predicted to be the second-lowest slot-cost option.

SENSITIVITIES: The analysis above places the nuclear power option tantalizingly close to the diesel baseline in total slot cost, and leads immediately to a few simplified sensitivity analyses.

Sensitivity to Fuel Price: Diesel fuel prices fluctuate. The sensitivity analysis shows that the slot cost of the diesel ship crosses over the cost of the nuclear ship once fuel rises to US$ 145/tonne.

Sensitivity to Range: This assessment shows the diesel ship to be quite insensitive to increasing range. The slot cost for the diesel varies across a range of less that one dollar despite a change in ship range from 1,000 miles to 12,000 mile. The nuclear plant, again using fixed assumptions, holds a constant slot cost of $12.23 for all ranges.

Sensitivity to Ship Speed: This assessment shows the two options (diesel and nuclear) running precisely parallel and 26% apart.

SUMMARY OF RESULTS

The analysis presented herein shows the nuclear electric powering alternative to be potentially within 20% of competitive with the baseline diesel plant. The gap between nuclear and diesel options decreases if petroleum prices rise, and it decreases slightly if ship range rises. And it is insensitive to speed.

1 INTRODUCTION

1.1 Administrative Background

This report was produced by Chris B. McKesson for the Center for Commercial Deployment of Transportation Technology (CCDOTT). The report documents a project to study the economic impact of alternative powering systems for container ships. The concept of the project is to assess whether there is economic incentive to develop alternative powering systems for container ships: Would such systems result in improved shipping economies?

This investigation is referred to as the CCDOTT Alternative Powering for Existing Ships project.

There is a similar CCDOTT project conducted simultaneously which considers the application of alternative powering schemes to proposed very-fast ships, specifically using the Fast Ship Atlantic project as a technology baseline. This larger project looks further over the horizon than does the present project, but there is nevertheless a significant interface between the two projects. The larger project is a contracted effort being performed by John J. McMullen Associates, Inc.

1.2 Purpose and Organization of this report

This report is the third of three deliverables of this project. The first report in this series presented an overview of the current state of the art of container ships, and the trends in their design. The second report presented an introduction to the range of alternative powering systems considered in this project. This third report completes the series by presenting an economic assessment of the impact of each of those alternative powering systems when applied to the notional baseline container ship derived from the trends in Report #1.

This report concludes with a summary of the economic impacts of each of the considered systems, along with some local sensitivity studies of those impacts. A recommendation for further study is presented.

2 APPLICATION OF ALTERNATIVE POWER TO A NOTIONAL CONTAINER SHIP

The previous reports in this series introduced the characteristics of the baseline container ship, and the trends in evolution expected in the next years (report #1). Also presented was an overview of alternative power plants and their characteristics (report #2).

In the present report these items "come together" into a simplified economic assessment of the various options in a notional container ship.

2.1 Baseline Ship

The Baseline container ship used in this economic assessment has characteristics as follows, as derived from the trends reported in Report #1 of this series.

Capacity	6000 teu
Service Speed	25 knots
Service Range	6000 nautical miles (unrefueled)
Power Required	75 MW

2.2 Economic Methodology

The application of alternative powerplants to the notional container ship has been handled parametrically. That is to say, that each powering option is analyzed on the basis of the following figures:

- kg / kW machinery weight
- kg / kW-h fuel consumption
- $ / kW acquisition cost
- $ / kW-h fuel cost

It is important to understand that this parametric methodology treats power plants as if they were "rubber", that is it treats them as if the linear parameter values can be equally applied at any power level. In fact, this is a simplification and real power plants can not be treated in this way. Real powerplants are available only in discrete sizes, and thus weights, costs, etc., demonstrate significant steps or jumps as one moves from one model to another.

Notwithstanding this remark, the "rubber engine" model is a common and appropriate model for feasibility investigations at the present level of simplification.

The next criticism that could be levied at this methodology would be that the parameter values are not realistic. In order to minimize this chance the present report uses parameter values that are, to the greatest extent possible, taken from published literature specific to the system in question. The intent is that the credibility of the parameter values will come from these source documents, and not from the author of this report.

Finally it should be noted that there is no parameter for manning-related costs. Manning costs are assumed to be constant for all powerplant options. We acknowledge that a more rigorous economic study would separately identify manning related costs, however this was felt to be outside the scope of the present effort. The present effort uses a very simplified “broad brush” approach to determine if there is indeed any economic incentive which might then warrant a more detailed assessment of one or more of the considered options.

2.3 Parameterization

The following paragraphs summarize the parameterization values used. Note that the origin or derivation of these values was given in report #2 of this project. The complete set of parameters is collected in Table 1 (top of next page)

2.3.1 Tonnes/kW

The weight of a given propulsion system is assessed by a kilograms-per-kilowatt parameter. Increases or decreases in weight compared to the diesel-mechanical baseline are treated as changes in the cargo capacity of the ship. We acknowledge that this is a simplification as it ignores the question of whether room is available for additional cargo, or conversely whether the ship should resized for a reduced payload.

Diesel Mechanical – 31.78 kg / kW

Turbine Mechanical – 1.5 – 3.8 kg / kW

Turbine Electric – 14.5 – 16.8 kg / kW

Nuclear Electric – 29.5 kg / kW

Fuel Cell Electric – 24.1 kg / kW

2.3.2 Tonnes-fuel/kW-hr

Cargo capacity is also impacted by the required ship fuel. The diesel baseline ship requires some 3000t of fuel. Changes from this baseline fuel load will result in increases or decreases in available cargo capacity. Note also, of course, that range determines fuel load. In subsequent sections of this report (Section 2.5.2.2) will be presented a sensitivity study of the impact of range.

In all cases, fuel weight is determined by applying a g/kw-h parameter which is treated as constant for each concept, as follows (next page): (See Report #2 for sources.)

Table 1 - Economic Parameters for Powering Alternatives

	Diesel Mechanical	Turbine Mechanical	Turbine Electric	Nuclear Electric	Fuel Cell Electric
Tonnes/kW	31.78 kg / kW	1.5 – 3.8 kg / kW	14.5 – 16.8 kg / kW	29.5 kg / kW	24.1 kg / kW
Tonnes-fuel/kW-hr	170 g / kW-hr	206 – 277 g / kW-hr	227 – 304 g / kW-hr	none	165-200 g / kW-hr
Acquisition $/kW	$175 / kW	$250 - $400 / kW	$300 - $500 / kW	$1,000/kW	$300 - $500/kW
Fuel $/kW-hr	$0.013 – $0.020	$0.030 – $0.050	$0.034 – $0.054	$0.016	$0.021 – $0.036

Diesel Mechanical: 170 g / kW-hr

Turbine Mechanical: 206 – 277 g / kW-hr

Turbine Electric: 227 – 304 g / kW-hr

Nuclear Electric: none

Fuel Cell Electric: 165-200 g / kW-hr

2.3.3 Acquisition $/kW

Acquisition cost is estimated on the basis of a simple $/kW parameter. This parameter is intended to contain all one-time costs, including required certification or unit disposal (in the case of the nuclear option) costs. Note that the cost used is for the Nth unit in series production, and does not include non-recurring costs for a prototype unit. Note further that this is acquisition of the propulsion plant only and does not include the ship. Since the ship acquisition costs will be common to all propulsion plants this was felt to be an appropriate simplification. This does ignore any situations in which the choice of one propulsion alternative will result in an increase or decrease in the cost of the rest of ship, say due to a very invasive installation, or a very simple modular installation. Again, such effects were felt to be second-order and best left for a subsequent study if the results of the present study were encouraging.

Diesel Mechanical – $175 / kW (source: personal communication with MAN B+W)

Turbine Mechanical – $250 - $400 / kW (source: Previous projects in 1991, inflated at 3% per year to 2000.)

Turbine Electric - $300 - $500 / kW (source: A rather gross assumption, allocating a 20-25% cost increase for the electric drive, and adjusting the turbine mechanical figures accordingly.)

Nuclear Electric – $1,000/kW (source: GT-MHR approximately $1000/kW based on South African Pebble Bed reactor, when produced in groups of ten. “Small Nuclear Power Reactors” UIC Nuclear Issues Briefing Paper # 60, November 2000.)

Fuel Cell Electric – $300 - $500/kW (This is a developmental item. Pricing is not known at this power level. Assumption has been made that prices will eventually be competitive with gas turbines. This assumption is not well founded, but may be sufficient for first explorations of gross ship economies.)

An immediate inspection of these figures shows that the penalty for the Nuclear option lies in its very high acquisition cost when compared to the conventional diesel option.

2.3.4 Fuel $/kW-hr

Fuel weight consumption rates above are translated into $/kW-hr rates by applying representative fuel costs. For low speed diesels burning heavy oil fuel price is taken as US$90 to US$120 per tonne. For gas turbine propulsion a lighter distillate fuel at US$150 to US$180 per tonne is used. Fuel cell fuel needs are not known at this time, but it seems clear they will require a low sulfur distillate fuel, not heavy fuel. We have therefore conducted the analysis across a range of fuel costs from US$130/t to US$180/t.

Applying these prices to the fuel consumption rates given in Report #2 results in fuel specific costs ($/kW-hr) as follows:

Diesel Mechanical – US$0.013 – US$0.020

Turbine Mechanical – US$0.030 – US$0.050

Turbine Electric – US$0.034 – US$0.054

Nuclear Electric – US$0.016 (source: GT-MHR total cost US$16/MWh – includes certification and decommissioning at end of life. “Small Nuclear Power Reactors” UIC Nuclear Issues Briefing Paper # 60, November 2000)

Fuel Cell Electric – US$0.021 – US$0.036

Fuel prices used above are based on world bunker prices reported in Fairplay, January of 2001.

2.3.5 Revenue Impacts

The mission of a container ship is to carry tonnes of cargo. Any system which reduces the lift capacity of the ship will reduce in direct proportion the revenue potential of the ship. Similarly, any system which reduces the weight of the propulsion plant will result in increased cargo lift capacity and thus increased revenue.

To account for this factor the weights of the alternative propulsion systems have been compared with the weights of the baseline low-speed diesel system. Any net change in weight (including weight of fuel) is applied to the revenue as follows:

Firstly, the weight of the propulsion alternative is compared to the weight of the diesel baseline. Any difference in weight is allocated to the ship as cargo capacity, according to an input value of homogenous container weight. Thus a propulsion option which is lighter in net than the diesel baseline will result in the ship having a cargo capacity greater than the 6000 teu for the baseline. Note that this methodology ignores issues of volume, and deals only with issues of weight.

Next, an input value of slot cost for the diesel baseline ship is provided. This input value is US$10/teu-day. This figure was obtained from American Ship Management Inc. in a private communication, as appropriate for a transpacific run at 25 knots.

The propulsion related costs described above are divided by the total slot-days for the ship, to arrive at a propulsion-fraction of slot cost. This fraction varies from propulsion alternative to propulsion alternative.

The non-propulsion portion of slot cost does not vary across propulsion alternatives. This cost is determined by subtracting the diesel baseline propulsion cost from the input market-rate slot cost. The subtraction leaves a residual slot cost which represents all portions of the ship not included in the propulsion cost estimate.

The non-propulsion portion of slot cost is expanded into a non-propulsion total cost by multiplying the slot-days times the non-propulsion slot cost, only for the baseline diesel ship. This figure is assumed to be constant for all propulsion alternatives, since it represents only non-propulsion elements of the ship.

The non-propulsion cost and the propulsion cost are summed. The total is then divided by the augmented slot-days for that propulsion alternative. Slot-days are augmented because the weights of the varying propulsion alternatives result in the delivery of more or less cargo weight to the ship.

The result of the calculation is a net slot cost prediction for each propulsion alternative.

2.4 Results

Review of the parameter table (Table 1) clearly shows that the low speed diesel is the lowest fuel consumption of any of the alternatives, and the lowest acquisition cost, with the penalty of being the heaviest. The question may then be stated as “does the weight reduction for any of the other choices compensate for increases in fuel or acquisition costs?” The economic analysis results are presented in Table 2. Each line of the table is explained in the “Method” column, and in the text below. As may be seen, the complete elimination of thousands of tonnes of fuel (via the nuclear option) does come close to closing the cost gap against the diesel option.

Table 2 - Economic Analysis of Propulsion Alternatives

				Diesel Mechanical		Turbine Mechanical		Turbine Electric		Nuclear Electric		Fuel Cell Electric	
Line Number			Method	Best	Worst	Best	Worst	Best	Worst	Best	Worst	Best	Worst
	SHIP PARAMETERS												
1	Ship Size	teu	input	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000
2	Ship Power Demand	kW	input	75000	75000	75000	75000	75000	75000	75000	75000	75000	75000
3	Trip Distance	nmi	input	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000
4	Trip Speed	knots	input	25	25	25	25	25	25	25	25	25	25
5	days underway per trip	days	input	10	10	10	10	10	10	10	10	10	10
6	Homo. Container Weight	t / teu	input	14	14	14	14	14	14	14	14	14	14
8	**MACHINERY PARAMETERS**												
9	tonnes / kW	kg / kW	input	31.78	31.78	1.5	3.8	14.5	16.8	29.5	29.5	24.1	24.1
10	tonnes fuel / kW-hr	g / kW-hr	input	170	170	206	277	227	304	0	0	165	200
11	Acquisition $ / kW	$ / kW	input	175	175	250	400	300	500	1000	1000	300	500
12	Fuel cost	$ / tonne	input	80	120	150	180	150	180			130	180
13	Fuel $ / kW-hr	$ / kW-hr	[10] x [12] / 1e6	0.0136	0.0204	0.0309	0.04986	0.03405	0.05472	0.016	0.024	0.02145	0.036
14	Other Operating $ / kW-hr	$ / kW-hr	input	0	0	0	0	0	0	0	0	0	0
15	kW-hr used	kW-hr / trip	[2] x [3] / [4]	18,000,000	18,000,000	18,000,000	18,000,000	18,000,000	18,000,000	18,000,000	18,000,000	18,000,000	18,000,000
16	Powerplant weight	tonnes	[2] x [9] / 1000	2383.5	2383.5	112.5	285	1087.5	1260	2212.5	2212.5	1807.5	1807.5
17	Fuel weight per trip	tonnes / trip	[15] x [10] / 1e6	3060	3060	3708	4986	4086	5472	0	0	2970	3600
18	total Propulsion Weight	tonnes / trip	[16] + [17]	5443.5	5443.5	3820.5	5271	5173.5	6732	2212.5	2212.5	4777.5	5407.5
19	Extra revenue capacity	tonnes	([18]-diesel) - ([18]-alternate)	0	0	1623	172.5	270	-1288.5	3231	3231	666	36
20	Extra revenue capacity	teu	[19] / [6]	0	0	116	12	19	-92	231	231	48	3
21	Augmented Ship Size	teu	[1] + [20]	6000	6000	6116	6012	6019	5908	6231	6231	6048	6003
22	**ECONOMIC PARAMETERS**												
23	interest rate	%	input	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
24	life span	years	input	25	25	25	25	25	25	25	25	25	25
25	Machinery Acquistion Cost	$	[2] x [11]	$ 13,125,000	$ 13,125,000	$ 18,750,000	$ 30,000,000	$ 22,500,000	$ 37,500,000	$ 75,000,000	$ 75,000,000	$ 22,500,000	$ 37,500,000
26	Acquisition cost per day	$/day	amortization based on [23]. [24], [25]	$3,918	$3,918	$5,597	$8,954	$6,716	$11,193	$22,386	$22,386	$6,716	$11,193
27	Fuel Cost per trip	$ / trip	[13] x [15]	$ 244,800.00	$ 367,200.00	$ 556,200.00	$ 897,480.00	$ 612,900.00	$ 984,960.00	$ 288,000.00	$ 432,000.00	$ 386,100.00	$ 648,000.00
28	Other Operating cost per trip	$ / trip	input	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
29	Acquisition cost per trip	$ / trip	[5] x [26]	$ 39,175.75	$ 39,175.75	$ 55,965.35	$ 89,544.56	$ 67,158.42	$ 111,930.70	$ 223,861.41	$ 223,861.41	$ 67,158.42	$ 111,930.70
30	TOTAL Propulsion Cost Per Trip	$ / trip	[27] + [28] + [29]	$ 283,975.75	$ 406,375.75	$ 612,165.35	$ 987,024.56	$ 680,058.42	$ 1,096,890.70	$ 511,861.41	$ 655,861.41	$ 453,258.42	$ 759,930.70
32	**SLOT COST**												
33	Slot Cost	$ / teu-day	input	$ 10.00	$ 10.00								
34	Machinery contribution to slot cost	$ / teu-day	[30]-diesel / ([5] x [21])	$ 4.73	$ 6.77								
35	Non-Propulsion portion of Slot Cost	$ / teu-day	[33] - [34]	$ 5.27	$ 3.23								
36	Built-up non propulsion cost	$ / trip	[35] x [5] x [21]	$ 316,024.25	$ 193,624.25	$ 193,624.25	$ 316,024.25	$ 193,624.25	$ 316,024.25	$ 193,624.25	$ 316,024.25	$ 193,624.25	$ 316,024.25
37	Total Ship Cost	$ / trip	[30] + [36]	$ 600,000.00	$ 600,000.00	$ 805,789.61	$ 1,303,048.82	$ 873,682.68	$ 1,412,914.96	$ 705,485.66	$ 971,885.66	$ 646,882.68	$ 1,075,954.96
38	Total Slot Cost	$ / teu-day	[37] / ([21] x [5])			$ 13.18	$ 21.67	$ 14.51	$ 23.92	$ 11.32	$ 15.60	$ 10.70	$ 17.92
39	Increase in slot cost	$ / teu-day	[38] - [33]-diesel			$ 3.18	$ 11.67	$ 4.51	$ 13.92	$ 1.32	$ 5.60	$ 0.70	$ 7.92

The calculations performed in Table 2 may be understood by careful study of the formulae given in the fourth column. The following remarks assist in such understanding:

1. Several items, designated "input", are of course the input parameters to the analysis. For each propulsion alternative two values are given – "best" and "worst" These values are as given in Section 2.3 above
2. For each option a fuel cost in dollars per tonne is given, per Section 2.3.4.
3. Ship power, ship range, and ship speed are inputs. These are arbitrary inputs selected to represent the "generic" container ship.
4. Acquisition cost is calculated by applying the $/kW parameter from Section 2.3.3 to the total ship power assumption.
5. Total kilowatt-hours used per crossing is calculated.
6. An interest rate and amortization period are assumed, in order to amortize acquisition cost to per-trip and per-day levels (given in the next two lines).
7. Powerplant weight and fuel weight are calculated from the t/kW and t/kW-hr parameters from 2.3.1 and 2.3.2 respectively. The sum of these two items (total propulsion weight) is compared to the total propulsion weight for the low speed diesel option, and the difference is presented as extra revenue capacity. Note that for some plants this figure may be negative (i.e. the alternative is a heavier system than the low speed diesel baseline.) Extra revenue capacity leads to a presentation of an "augmented ship size" (item [21]) which expresses the total as a value of TEUs.
8. Cost and revenue factors are applied to the parameters calculated thus far, and the results are totaled to a net total per trip, and a net slot cots (best and worst for each propulsion alternative) is calculated.

2.5 Economic Comparison of Alternative Results

Several sets of results are presented, using the methodology described. First, under 2.5.1, are the general results from the initial assumptions, corresponding to the calculations presented in Table 2. Analysis and discussion of these general results rapidly raises questions which lead to secondary analyses and sensitivity studies. These secondary analyses are presented in sections 2.5.2.1 through 2.5.2.3

2.5.1 General Results

According to the above methodology, the total cost to move a 75 MW diesel direct drive container ship across 6,000 nautical miles at 25 knots is approximately $600,000. Of this an estimated US$283,000 to US$406,000 is propulsion related, including fuel and acquisition of the engines. The remaining US$193,000 to US$316,000 is related to acquisition and operation of the non-propulsion portions of the ship. These figures correspond to a total slot cost of US$10 per teu-day.

A gas turbine driven ship suffers a 30% to 120% penalty. The economic picture of the turbine is greatly influenced by fuel cost. The gas turbine consumes more fuel than the baseline diesel, and this fuel is higher priced than that consumed by the diesel. This fuel also appears from the data found by this author to be subject to a wider range of prices than the diesel fuel. This sort of cost volatility has driven turbines out of some other trades in the past. The gas turbine analysis takes into account the prediction that a turbine-driven ship could have a higher cargo capacity. The present analysis shows the turbine's weight savings (net after accounting for fuel load) result in between ten and one hundred extra teu capacity.

A gas turbine-electric drive system is economically worse than the turbine mechanical drive, due to the added cost for the electric transmission, and the increase in power required due to the electrical transmission efficiency. Indeed, under the worst assumptions a turbine electric drive system ends up heavier than the baseline diesel system, as well as more costly. Under the best assumptions the system is slightly lighter than the diesel, with a net 19 teu increase in lift capacity, but this does not markedly compensate for a $300-$400,000 increase in per trip cost.

The nuclear-electric option is the lightest weight of all the options. It returns as many as 231 additional teu to the ship, a 4% increase in revenue capacity. Further, under the best assumptions the nuclear option is only about $105,000 per trip more expensive than the diesel baseline. As a result of the teu increase this cost increase is leveraged downward, such that the best-assumptions Nuclear slot cost is only $11.32. This is the lowest slot cost of any of the considered propulsion alternatives. Indeed, it is sufficiently close to the diesel baseline figure to suggest several sensitivity analyses which will be explored below.

Note that the above paragraph applies only to the "best assumptions" nuclear option. The "worst-assumptions" version of the nuclear option results in a slot cost of $13.29, a 33% increase over the baseline.

The fuel cell alternative appears attractive if it can use a less expensive fuel oil and if acquisition costs can be as low as has been assumed. If it requires more expensive lighter distillate fuel oil, and comes in at the high end of acquisition cost, then it may be very unattractive. The advantage of the fuel cell lies in its lower specific fuel consumption (SFC) compared to the diesel. The disadvantage of the fuel cell lies in the complexity of its electric transmission components, and of course cost and scalability uncertainty at this time.

The cost estimates for all alternatives, showing best, worst, and average, are presented graphically in Figure 1.

At first glance these results would indicated that container ships should be diesel propelled, and indeed the market decisions made daily have already reached this conclusion. The results have also, however, produced some intriguing possibilities and raised some questions that will be explored in the sections which follow.

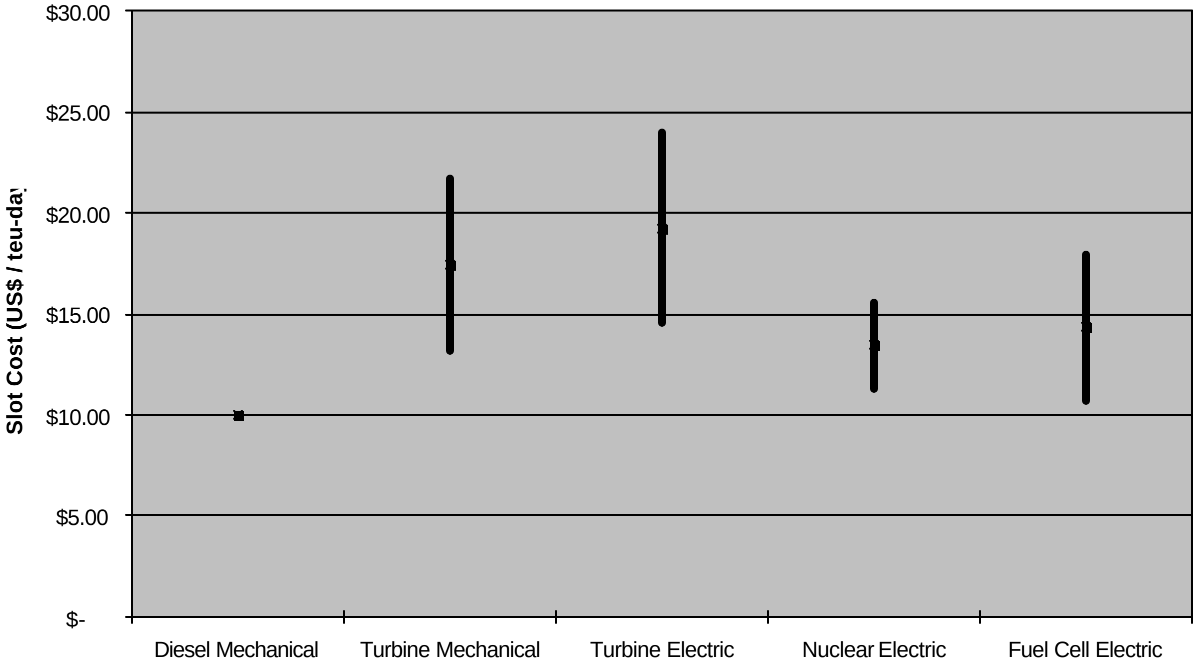

Figure 1 - Comparison of Total Slot Cost for all propulsion alternatives - 6000 nmi @ 25 knots, 6000 teu Baseline

---

2.5.2 Sensitivity Studies

The analysis above places the nuclear power option tantalizingly close to the diesel baseline in total slot cost. What would it take to close the gap? Are there any circumstances in which the nuclear option would be lower priced than the diesel option? These questions have been touched upon by a series of sensitivity studies using the model.

Sensitivity studies which have been performed are:

- To what extent does the conclusions depend upon fuel prices?
- To what extent are the conclusions driven by the magnitude of the ship's fuel load, i.e. the ship's range?
- What if the speed were increased?

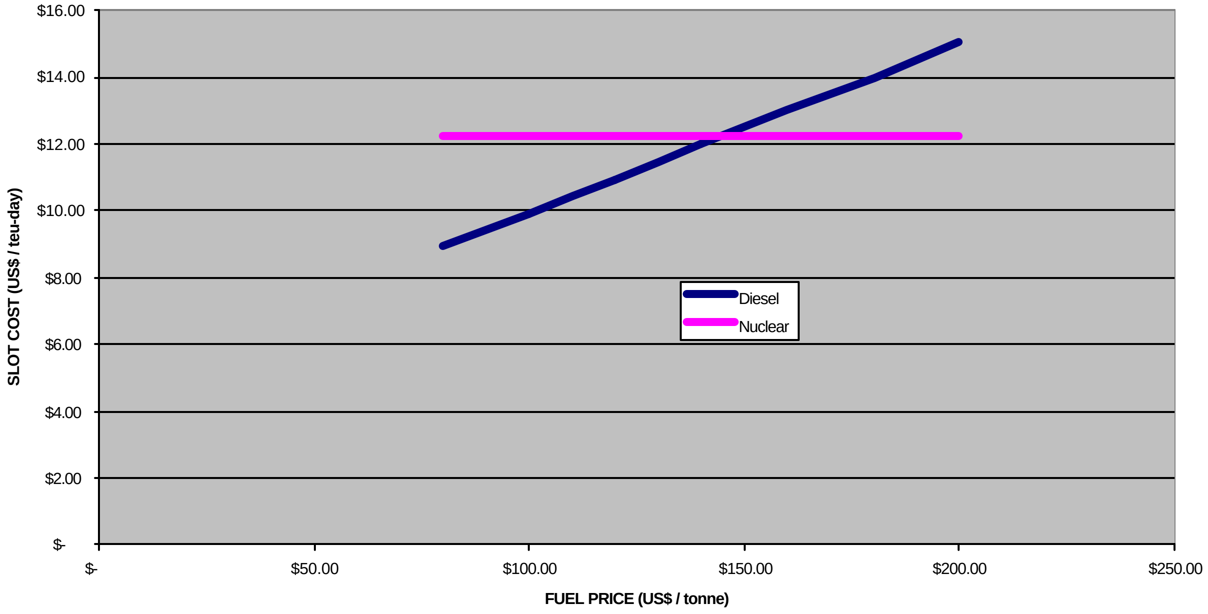

Figure 2 - Slot Cost sensitivity to Fuel Price - Diesel and Nuclear alternatives only

---

2.5.2.1 Sensitivity to Fuel Price

Diesel fuel prices fluctuate. It is not difficult to imagine a scenario – say, war in the Middle East – which would result in a 50% increase in the cost of diesel fuel. The effect of such an event is shown in Figure 2, where the slot cost of a diesel propelled ship is plotted against a range of fuel prices.

The calculation that underlies this graph was performed using a single median value for Non-Propulsion costs, fixed at US $ 25,000 / day (parameter [36] in Table 1.) This value results in a nuclear slot cost of $12.23, about the middle of the "best / worst" range given above.

As may be seen in the figure, the slot cost of the diesel ship crosses over the cost of the nuclear ship once fuel rises to US$ 145/tonne.

2.5.2.2 Sensitivity to Range

The sensitivity to range is interesting – see Figure 3. This shows the diesel ship to be quite insensitive to increasing range. The slot cost for the diesel varies across a range of less that one dollar despite a change in ship range from 1,000 miles to 12,000 mile. The nuclear plant, again using fixed assumptions, holds a constant slot cost of $12.23 for all ranges.

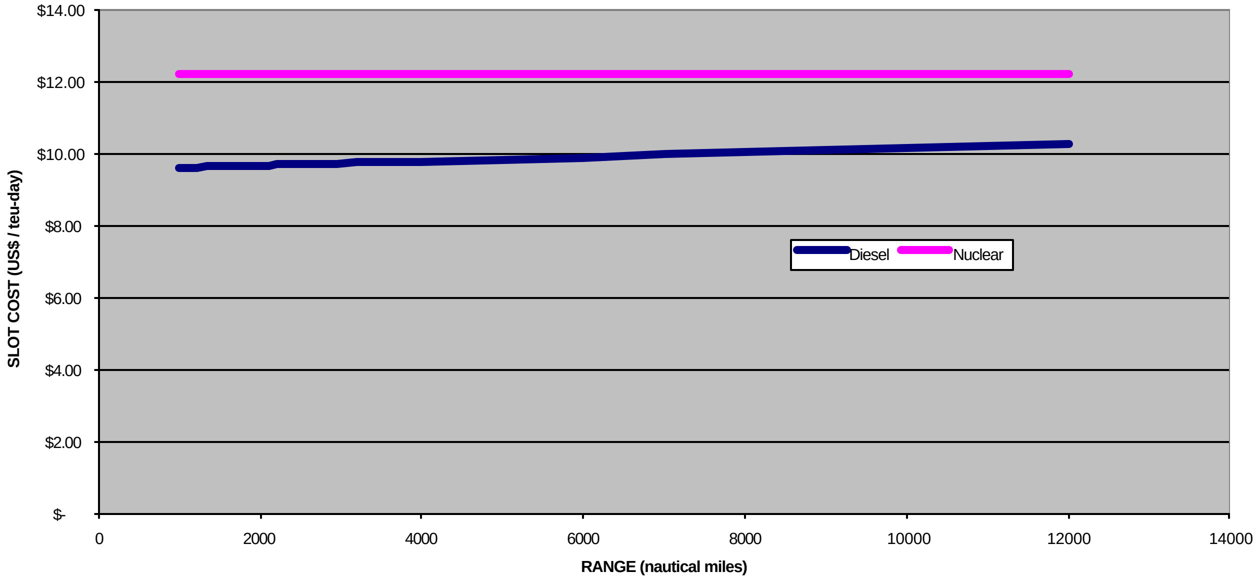

Figure 3 - Slot Cost sensitivity to Range. Diesel and Nuclear alternatives only.

2.5.2.3 Sensitivity to Ship Speed

In this analysis, ship power has been assumed to vary as the cube of speed. If, then, 75 MW are required for 25 knots of speed, then the resulting formula is P = 4.8 V^3

Applying this formula in the economic model to a range of speeds from 25 to 35 knots, yields the results plotted in Figure 4

Surprisingly this figure shows the two options (diesel and nuclear) running precisely parallel and 26% apart. This is surprising, as one might have expected the cubic growth in diesel fuel load weight to come to dominate the picture at very high power levels. This turns out not to be the case, however, because the nuclear reactor plant total system also grows as the cube of ship speed, and the two exactly maintain pace with each other.

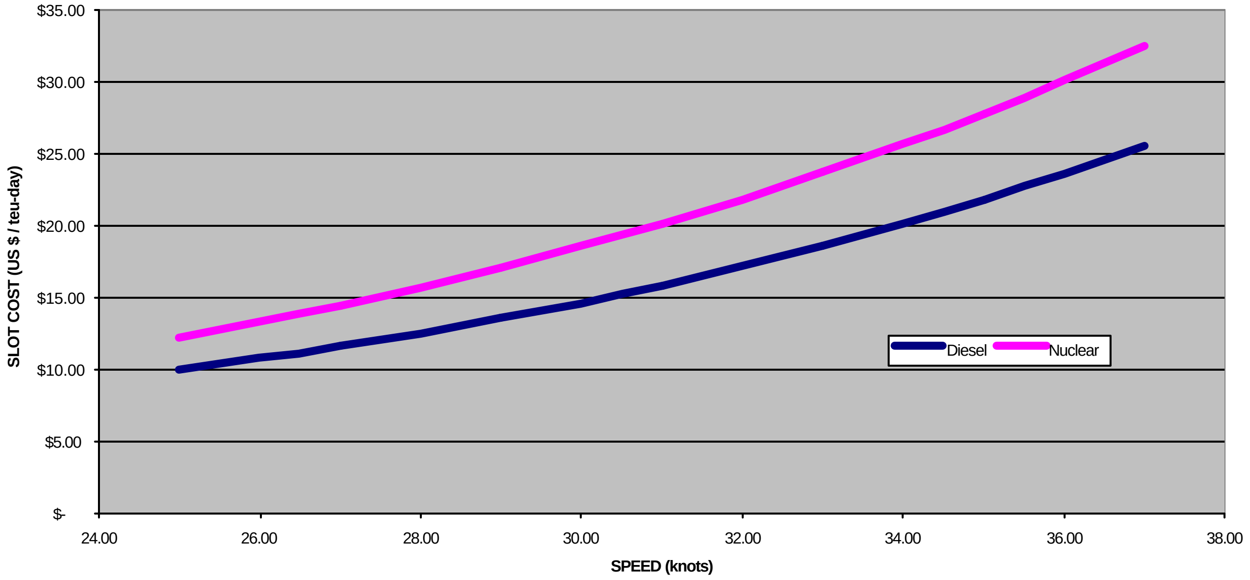

Figure 4 - Slot Cost sensitivity to Ship Speed. Diesel and Nuclear alternatives only.

3 SUMMARY OF RESULTS

3.1 Conclusions

The analysis presented herein has shown the nuclear electric powering alternative to be potentially within 20% of the baseline diesel plant.

Gas turbine power is markedly economically inferior to the direct drive low-speed diesel. This result accords perfectly with the observed facts of the marketplace, wherein gas turbine container ships are nonexistent.

The introduction of electric transmission (e.g. gas turbine – electric drive) worsens the economic gap, due to the inefficiencies and weight impacts of the electric transmission components. This too is perhaps obvious.

The fuel cell alternative may be competitive, if the fuel cell can be made to operate on low-priced fuel, and if the fuel cell acquisition costs are as low as other competing systems. The fuel cell's competitiveness arises from its high efficiency, expressed as a very low SFC.

The key to the nuclear plant's competitiveness seems to be associated with the reduction of plant weight compared to the diesel-plus-fuel baseline.

The gap between nuclear and diesel options decreases if petroleum prices rise, and it decreases slightly if ship range rises. It appears to be insensitive to ship speed.

3.2 Recommendations for further study

The conclusions above show that the nuclear option is surprisingly close in economic merit to the current diesel baseline. This conclusion has been reached even though the system in which the plant is used – the modern container ship – is a system very closely optimized and built around the diesel engine. If the nuclear plant is this close to competitive in such a baseline, would it become more competitive if some of the basis constraints were relaxed? Would the nuclear plant be more competitive in extreme ship sizes, such as the 10,000 teu ULCS that are forecast? What about a future mission consisting of very large capacity (say 10,000-12,000 teu) very long range (say 10,000) miles and high speed (say 32 knots)?

These and similar design points are recommended for further study.

The point to be taken is that the nuclear plant appears to be surprisingly competitive in a system finely tuned for the diesel. Would it be even more competitive under slightly modified assumptions?

4 Appendix A: Calculations of Sensitivity to Fuel Price

				Diesel Mechanical							Nuclear Electric	
Line Number			Method	Best						Worst	Best	Worst
	SHIP PARAMETERS											
1	Ship Size	teu	input	6000	6000	6000	6000	6000	6000	6000	6000	6000
2	Ship Power Demand	kW	input	75000	75000	75000	75000	75000	75000	75000	75000	75000
3	Trip Distance	nmi	input	6000	6000	6000	6000	6000	6000	6000	6000	6000
4	Trip Speed	knots	input	25	25	25	25	25	25	25	25	25
5	days underway per trip	days	input	10	10	10	10	10	10	10	10	10
6	Homo. Container Weight	t / teu	input	14	14	14	14	14	14	14	14	14
8	**MACHINERY PARAMETERS**											
9	tonnes / kW	kg / kW	input	31.78	31.78	31.78	31.78	31.78	31.78	31.78	29.5	29.5
10	tonnes fuel / kW-hr	g / kW-hr	input	170	170	170	170	170	170	170	0	0
11	Acquisition $ / kW	$ / kW	input	175	175	175	175	175	175	175	1000	1000
12	Fuel cost	$ / tonne	input	80	100	120	140	160	180	200		
13	Fuel $ / kW-hr	$ / kW-hr	[10] x [12] / 1e6	0.0136	0.017	0.0204	0.0238	0.0272	0.0306	0.034	0.016	0.016
14	Other Operating $ / kW-hr	$ / kW-hr	input	0	1	2	3	4	5	0	0	0
15	kW-hr used	kW-hr / trip	[2] x [3] / [4]	18,000,000	18,000,000	18,000,000	18,000,000	18,000,000	18,000,000	18,000,000	18,000,000	18,000,000
16	Powerplant weight	tonnes	[2] x [9] / 1000	2383.5	2383.5	2383.5	2383.5	2383.5	2383.5	2383.5	2212.5	2212.5
17	Fuel weight per trip	tonnes / trip	[15] x [10] / 1e6	3060	3060	3060	3060	3060	3060	3060	0	0
18	total Propulsion Weight	tonnes / trip	[16] + [17]	5443.5	5443.5	5443.5	5443.5	5443.5	5443.5	5443.5	2212.5	2212.5
19	Extra revenue capacity	tonnes	([18]-diesel) - ([18]-alternate)	0	0	0	0	0	0	0	3231	3231
20	Extra revenue capacity	teu	[19] / [6]	0	0	0	0	0	0	0	231	231
21	Augmented Ship Size	teu	[1] + [20]	6000	6000	6000	6000	6000	6000	6000	6231	6231
22	**ECONOMIC PARAMETERS**											
23	interest rate	%	input	10%	10%	10%	10%	10%	10%	10%	10%	10%
24	life span	years	input	25	25	25	25	25	25	25	25	25
25	Machinery Acquistion Cost	$	[2] x [11]	$ 13,125,000	$ 13,125,000	$ 13,125,000	$ 13,125,000	$ 13,125,000	$ 13,125,000	$ 13,125,000	$ 75,000,000	$ 75,000,000
26	Acquisition cost per day	$/day	amortization based on [23]. [24], [25]	$3,918	$3,918	$3,918	$3,918	$3,918	$3,918	$3,918	$22,386	$22,386
27	Fuel Cost per trip	$ / trip	[13] x [15]	$ 244,800.00	$ 306,000.00	$ 367,200.00	$ 428,400.00	$ 489,600.00	$ 550,800.00	$ 612,000.00	$ 288,000.00	$ 288,000.00
28	Other Operating cost per trip	$ / trip	input	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
29	Acquisition cost per trip	$ / trip	[5] x [26]	$ 39,175.75	$ 39,175.75	$ 39,175.75	$ 39,175.75	$ 39,175.75	$ 39,175.75	$ 39,175.75	$ 223,861.41	$ 223,861.41
30	TOTAL Propulsion Cost Per Trip	$ / trip	[27] + [28] + [29]	$ 283,975.75	$ 345,175.75	$ 406,375.75	$ 467,575.75	$ 528,775.75	$ 589,975.75	$ 651,175.75	$ 511,861.41	$ 511,861.41
32	**SLOT COST**											
36	Built-up non propulsion cost	$ / trip	[35] x [5] x [21]	$ 250,000.00	$ 250,000.00	$ 250,000.00	$ 250,000.00	$ 250,000.00	$ 250,000.00	$ 250,000.00	$ 250,000.00	$ 250,000.00
37	Total Ship Cost	$ / trip	[30] + [36]	$ 533,975.75	$ 595,175.75	$ 656,375.75	$ 717,575.75	$ 778,775.75	$ 839,975.75	$ 901,175.75	$ 761,861.41	$ 761,861.41
38	Total Slot Cost	$ / teu-day	[37] / ([21] x [5])	$ 8.90	$ 9.92	$ 10.94	$ 11.96	$ 12.98	$ 14.00	$ 15.02	$ 12.23	$ 12.23

5 Appendix B: Calculations of Sensitivity to Range

			Diesel Mechanical							Nuclear Electric						
Line Number			Best						Worst	Best						Worst
	SHIP PARAMETERS															
1	Ship Size	teu	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000
2	Ship Power Demand	kW	75000	75000	75000	75000	75000	75000	75000	75000	75000	75000	75000	75000	75000	75000
3	Trip Distance	nmi	1000	2000	4000	6000	8000	10000	12000	1000	2000	4000	6000	8000	10000	12000
4	Trip Speed	knots	25	25	25	25	25	25	25	25	25	25	25	25	25	25
5	days underway per trip	days	1.666666667	3.333333333	6.666666667	10	13.33333333	16.66666667	20	1.666666667	3.333333333	6.666666667	10	13.33333333	16.66666667	20
6	Homo. Container Weight	t / teu	14	14	14	14	14	14	14	14	14	14	14	14	14	14
8	**MACHINERY PARAMETERS**															
9	tonnes / kW	kg / kW	31.78	31.78	31.78	31.78	31.78	31.78	31.78	29.5	29.5	29.5	29.5	29.5	29.5	29.5
10	tonnes fuel / kW-hr	g / kW-hr	170	170	170	170	170	170	170	0	0	0	0	0	0	0
11	Acquisition $ / kW	$ / kW	175	175	175	175	175	175	175	1000	1000	1000	1000	1000	1000	1000
12	Fuel cost	$ / tonne	100	100	100	100	100	100	100							
13	Fuel $ / kW-hr	$ / kW-hr	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.016	0.016	0.016	0.016	0.016	0.016	0.016
14	Other Operating $ / kW-hr	$ / kW-hr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	kW-hr used	kW-hr / trip	3,000,000	6,000,000	12,000,000	18,000,000	24,000,000	30,000,000	36,000,000	3,000,000	6,000,000	12,000,000	18,000,000	24,000,000	30,000,000	36,000,000
16	Powerplant weight	tonnes	2383.5	2383.5	2383.5	2383.5	2383.5	2383.5	2383.5	2212.5	2212.5	2212.5	2212.5	2212.5	2212.5	2212.5
17	Fuel weight per trip	tonnes / trip	510	1020	2040	3060	4080	5100	6120	0	0	0	0	0	0	0
18	total Propulsion Weight	tonnes / trip	2893.5	3403.5	4423.5	5443.5	6463.5	7483.5	8503.5	2212.5	2212.5	2212.5	2212.5	2212.5	2212.5	2212.5
19	Extra revenue capacity	tonnes	2550	2040	1020	0	-1020	-2040	-3060	3231	3231	3231	3231	3231	3231	3231
20	Extra revenue capacity	teu	182	146	73	0	-73	-146	-219	231	231	231	231	231	231	231
21	Augmented Ship Size	teu	6182	6146	6073	6000	5927	5854	5781	6231	6231	6231	6231	6231	6231	6231
22	**ECONOMIC PARAMETERS**															
23	interest rate	%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
24	life span	years	25	25	25	25	25	25	25	25	25	25	25	25	25	25
25	Machinery Acquistion Cost	$	$ 13,125,000	$ 13,125,000	$ 13,125,000	$ 13,125,000	$ 13,125,000	$ 13,125,000	$ 13,125,000	$ 75,000,000	$ 75,000,000	$ 75,000,000	$ 75,000,000	$ 75,000,000	$ 75,000,000	$ 75,000,000
26	Acquisition cost per day	$/day	$3,918	$3,918	$3,918	$3,918	$3,918	$3,918	$3,918	$22,386	$22,386	$22,386	$22,386	$22,386	$22,386	$22,386
27	Fuel Cost per trip	$ / trip	$ 51,000.00	$ 102,000.00	$ 204,000.00	$ 306,000.00	$ 408,000.00	$ 510,000.00	$ 612,000.00	$ 48,000.00	$ 96,000.00	$ 192,000.00	$ 288,000.00	$ 384,000.00	$ 480,000.00	$ 576,000.00
28	Other Operating cost per trip	$ / trip	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
29	Acquisition cost per trip	$ / trip	$ 6,529.29	$ 13,058.58	$ 26,117.16	$ 39,175.75	$ 52,234.33	$ 65,292.91	$ 78,351.49	$ 37,310.23	$ 74,620.47	$ 149,240.94	$ 223,861.41	$ 298,481.88	$ 373,102.35	$ 447,722.82
30	TOTAL Propulsion Cost Per Trip	$ / trip	$ 57,529.29	$ 115,058.58	$ 230,117.16	$ 345,175.75	$ 460,234.33	$ 575,292.91	$ 690,351.49	$ 85,310.23	$ 170,620.47	$ 341,240.94	$ 511,861.41	$ 682,481.88	$ 853,102.35	$ 1,023,722.82
32	**SLOT COST**															
36	Built-up non propulsion cost	$ / trip	$ 41,666.67	$ 83,333.33	$ 166,666.67	$ 250,000.00	$ 333,333.33	$ 416,666.67	$ 500,000.00	$ 41,666.67	$ 83,333.33	$ 166,666.67	$ 250,000.00	$ 333,333.33	$ 416,666.67	$ 500,000.00
37	Total Ship Cost	$ / trip	$ 99,195.96	$ 198,391.92	$ 396,783.83	$ 595,175.75	$ 793,567.66	$ 991,959.58	$ 1,190,351.49	$ 126,976.90	$ 253,953.80	$ 507,907.61	$ 761,861.41	$ 1,015,815.21	$ 1,269,769.01	$ 1,523,722.82
38	Total Slot Cost	$ / teu-day	$ 9.63	$ 9.68	$ 9.80	$ 9.92	$ 10.04	$ 10.17	$ 10.29	$ 12.23	$ 12.23	$ 12.23	$ 12.23	$ 12.23	$ 12.23	$ 12.23

6 Appendix C: Calculations of Sensitivity to Ship Speed

			Diesel Mechanical							Nuclear Electric						
Line Number			Best						Worst	Best						Worst
	SHIP PARAMETERS															
1	Ship Size	teu	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000
2	Ship Power Demand	kW	75000	94478.4	117067.2	142996.8	172497.6	205800	243,134.40	75000	94478.4	117067.2	142996.8	172497.6	205800	243,134.40
3	Trip Distance	nmi	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000
4	Trip Speed	knots	25	27	29	31	33	35	37	25	27	29	31	33	35	37
5	days underway per trip	days	10	9.259259259	8.620689655	8.064516129	7.575757576	7.142857143	6.756756757	10	9.259259259	8.620689655	8.064516129	7.575757576	7.142857143	6.756756757
6	Homo. Container Weight	t / teu	14	14	14	14	14	14	14	14	14	14	14	14	14	14
8	**MACHINERY PARAMETERS**															
9	tonnes / kW	kg / kW	31.78	31.78	31.78	31.78	31.78	31.78	31.78	29.5	29.5	29.5	29.5	29.5	29.5	29.5
10	tonnes fuel / kW-hr	g / kW-hr	170	170	170	170	170	170	170	0	0	0	0	0	0	0
11	Acquisition $ / kW	$ / kW	175	175	175	175	175	175	175	1000	1000	1000	1000	1000	1000	1000
12	Fuel cost	$ / tonne	100	100	100	100	100	100	100							
13	Fuel $ / kW-hr	$ / kW-hr	0.017	0.017	0.017	0.017	0.017	0.017	0.017	0.016	0.016	0.016	0.016	0.016	0.016	0.016
14	Other Operating $ / kW-hr	$ / kW-hr	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	kW-hr used	kW-hr / trip	18,000,000	20,995,200	24,220,800	27,676,800	31,363,200	35,280,000	39,427,200	18,000,000	20,995,200	24,220,800	27,676,800	31,363,200	35,280,000	39,427,200
16	Powerplant weight	tonnes	2383.5	3002.523552	3720.395616	4544.438304	5481.973728	6540.324	7726.811232	2212.5	2787.1128	3453.4824	4218.4056	5088.6792	6071.1	7172.4648
17	Fuel weight per trip	tonnes / trip	3060	3569.184	4117.536	4705.056	5331.744	5997.6	6702.624	0	0	0	0	0	0	0
18	total Propulsion Weight	tonnes / trip	5443.5	6571.707552	7837.931616	9249.494304	10813.71773	12537.924	14429.43523	2212.5	2787.1128	3453.4824	4218.4056	5088.6792	6071.1	7172.4648
19	Extra revenue capacity	tonnes	0	-1128.207552	-2394.431616	-3805.994304	-5370.217728	-7094.424	-8985.935232	3231	2656.3872	1990.0176	1225.0944	354.8208	-627.6	-1728.9648
20	Extra revenue capacity	teu	0	-81	-171	-272	-384	-507	-642	231	190	142	88	25	-45	-123
21	Augmented Ship Size	teu	6000	5919	5829	5728	5616	5493	5358	6231	6190	6142	6088	6025	5955	5877
22	**ECONOMIC PARAMETERS**															
23	interest rate	%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
24	life span	years	25	25	25	25	25	25	25	25	25	25	25	25	25	25
25	Machinery Acquistion Cost	$	$ 13,125,000	$ 16,533,720	$ 20,486,760	$ 25,024,440	$ 30,187,080	$ 36,015,000	$ 42,548,520	$ 75,000,000	$ 94,478,400	###########	###########	$ 172,497,600	$ 205,800,000	$ 243,134,400
26	Acquisition cost per day	$/day	$3,918	$4,935	$6,115	$7,469	$9,010	$10,750	$12,700	$22,386	$28,200	$34,942	$42,682	$51,487	$61,428	$72,571
27	Fuel Cost per trip	$ / trip	$ 306,000.00	$ 356,918.40	$ 411,753.60	$ 470,505.60	$ 533,174.40	$ 599,760.00	$ 670,262.40	$ 288,000.00	$ 335,923.20	$ 387,532.80	$ 442,828.80	$ 501,811.20	$ 564,480.00	$ 630,835.20
28	Other Operating cost per trip	$ / trip	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
29	Acquisition cost per trip	$ / trip	$ 39,175.75	$ 45,694.59	$ 52,714.88	$ 60,236.63	$ 68,259.82	$ 76,784.46	$ 85,810.56	$ 223,861.41	$ 261,111.95	$ 301,227.91	$ 344,209.30	$ 390,056.12	$ 438,768.36	$ 490,346.03
30	TOTAL Propulsion Cost Per Trip	$ / trip	$ 345,175.75	$ 402,612.99	$ 464,468.48	$ 530,742.23	$ 601,434.22	$ 676,544.46	$ 756,072.96	$ 511,861.41	$ 597,035.15	$ 688,760.71	$ 787,038.10	$ 891,867.32	$ 1,003,248.36	$ 1,121,181.23
32	**SLOT COST**															
36	Built-up non propulsion cost	$ / trip	$ 250,000.00	$ 231,481.48	$ 215,517.24	$ 201,612.90	$ 189,393.94	$ 178,571.43	$ 168,918.92	$ 250,000.00	$ 231,481.48	$ 215,517.24	$ 201,612.90	$ 189,393.94	$ 178,571.43	$ 168,918.92
37	Total Ship Cost	$ / trip	$ 595,175.75	$ 634,094.47	$ 679,985.73	$ 732,355.13	$ 790,828.16	$ 855,115.89	$ 924,991.87	$ 761,861.41	$ 828,516.63	$ 904,277.95	$ 988,651.00	$ 1,081,261.26	$ 1,181,819.79	$ 1,290,100.15
38	Total Slot Cost	$ / teu-day	$ 9.92	$ 11.57	$ 13.53	$ 15.85	$ 18.59	$ 21.79	$ 25.55	$ 12.23	$ 14.46	$ 17.08	$ 20.14	$ 23.69	$ 27.78	$ 32.49

7 Appendix D: UIC Nuclear Issues Briefing Paper # 60 - November 2000

Small Nuclear Power Reactors

UIC Nuclear Issues Briefing Paper # 60

November 2000

- ***There is revival of interest in small and simpler units for generating electricity from nuclear power.***
- ***This is driven both by a desire to reduce capital costs and to provide power away from main grid systems.***
- ***The leading technologies use high temperature helium to drive turbines directly.***

As nuclear power generation has become established since the 1950s, the size of reactor units has grown from 60 MWe to more than 1300 MWe, with corresponding economies of scale in operation. At the same time there have been many hundreds of smaller reactors built both for naval use (up to 190 MW thermal) and as neutron sources, yielding enormous expertise in the engineering of deliberately small units.

Today, due partly to the high capital cost of large power reactors generating electricity via the steam cycle and partly to consideration of public perception, there is a move to develop smaller units which may be built independently or as modules in a larger complex, with capacity added incrementally as required.

The most prominent project in this category is the South African-led consortium developing the Pebble Bed Modular Reactor of 110 MWe. A US-led group is developing another design with 285 MWe modules. Both drive gas turbines directly, using helium as a coolant and operating at very high temperatures. They build on the experience of several innovative reactors in the 1960s and 1970s.

Generally, modern small reactors for power generation are expected to have greater simplicity of design, economy of mass production, and reduced siting costs. Many are also designed for a high level of passive safety in the event of malfunction. Some are conceived for areas away from transmission grids and with small loads, others are designed to operate in clusters in competition with large units.

US Congress is now starting to fund research on both small modular nuclear power plants and advanced gas-cooled designs.

Already operating in a remote corner of Siberia are four small units at the Bilibino co-generation plant. These four 62 MW (thermal) units are an unusual graphite-moderated boiling water design with water/steam channels through the moderator. They produce steam for district heating and 11 MWe (net) electricity each. They have performed well since 1976, much more cheaply than fossil fuel alternatives in the Arctic region.

7.1.1 Light Water Reactors

US experience has been of very small military power plants, such as the 11 MW (thermal), 1.5 MWe (net) PM-3A reactor which operated at McMurdo Sound in Antarctica 1962-72, generating a total of 78 million kWh.

The Russian KLT-40 is a reactor well proven in icebreakers and now proposed for wider use in desalination and, on barges, for remote area power supply where it produces 30 MWe (net) as well as heat. While these are designed to run 3-4 years between refuelling it is envisaged that they will be operated in pairs to allow for outages. One option is to have on-board refuelling capability with spent fuel storage.

The CAREM (advanced small nuclear power plant) being developed by INVAP in Argentina is a modular 100 MW thermal pressurised water reactor with integral steam generators designed to be used for electricity generation (25 MWe) or as a research reactor or for water desalination.

South Korea's 330 MW thermal SMART (System-integrated modular advanced reactor) is a pressurised water reactor with integral steam generators and advanced safety features. It is designed for generating electricity (up to 100 MWe) and/or thermal applications such as seawater desalination.

Japan is studying a small (50-300 MW thermal) reactor of marine propulsion or local energy supply.

Small reactors under development

CAREM-25	25 MWe PWR	INVAP, Argentina
KLT-40	40 MWe PWR	OKBM, Russia
SMART	100 MWe PWR	KAERI, S. Korea
PBMR	110 MWe HTGR	Eskom, South Africa, et al
GT-MHR	285 MWe HTGR	General Atomics (USA), Minatom (Russia) et al

7.1.2 High-temperature Gas-cooled reactors

South Africa's Pebble Bed Modular Reactor (PBMR) with a direct-cycle gas turbine generator is being developed by a consortium led by the utility Eskom, drawing on German expertise. Modules will be of 110 MWe and thermal efficiency about 42-50%. Fuel consists of tennis ball sized pebbles of graphite moderator containing 8% enriched UO2 and coated with silicon carbide. The 330,000 fuel pebbles recycle through the reactor continuously until they are expended, giving an average enrichment in the fuel load of 5-6% and burn-up of 80,000 MWday/t U. Each unit will finally discharge about 19 tonnes of spent pebbles per year to ventilated on-site storage bins.

Construction cost (when in clusters of ten units) is expected to be US$ 1000/kW and generating cost 1.6 US cents/kWh. Eskom and the South African Industries Development Corporation hold 55% of the project, with BNFL 20% and Exelon 10%. A scale model criticality test was carried out in Moscow in 1999 and a prototype is due to be built in 2001 to start operation in 2005.

A larger US design, the Gas Turbine - Modular Helium Reactor (GT-MHR), will be built as modules of 285 MWe each. Its fuel is ceramic-coated particles incorporated into hexagonal graphite blocks or 'prisms', giving it a high level of inherent safety. It will directly drive a gas turbine at almost 50% thermal efficiency.

It is being developed by General Atomics in partnership with Russia's Minatom, and initially will be used to burn pure ex-weapons plutonium in Russia. In 1996-97 Framatome (France) and Fuji (Japan) joined the development consortium. The detailed design stage is complete and some component testing has started. Plant costs are expected to be less than US$ 1000/kW.

Sources:

IAEA Nuclear Technology Review 2000.
Mourogov, V., 2000, The need for innovative nuclear reactor and fuel cycle systems, UI Symposium.
UIC briefing paper # 16.

Uranium Information Centre Ltd
A.B.N. 30 005 503 828

GPO Box 1649N, Melbourne 3001, Australia
phone (03) 9629 7744
fax (03) 9629 7207
E-mail : *uic@mpx.com.au*