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AN ECONOMIC ANALYSIS OF THE DOMESTIC AND OVERSEAS SHIPMENT OF SPENT REACTOR FUEL

L. B. Shappert

ABSTRACT

The cost of shipping spent reactor fuel from a domestic and foreign natural uranium reactor to a reprocessing plant in the U.S. was investigated. The domestic reactor was located at Point Loma, Calif., and the spent fuel was shipped 1176 miles to Hanford, Wash. The foreign reactor was located in Italy, and the spent fuel was shipped to Southern California. Two reactors were considered: one with thermal power of 3500Mw (case 1, domestic only) and the other was a 25,000-Mw reactor (case 2).

The total shipping cost was assumed to be made up of (1) freight charges, (2) depreciation charges on capital equipment, (3) handling charges, and (4) insurance charges. Each of these costs is discussed.

Results indicated that for the largest reactor (case 2) situated in the U.S., truck transportation was the cheapest practical method: $1.30 per kilogram of uranium shipped under the conditions specified. Using the same relatively small 13-element
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cask, transportation by rail would cost $2.23 per kilogram of uranium. A larger, 48-element cask, when shipped by rail (which might be a questionable procedure due to the high heat load) would bring the unit cost down to $1.67 per kilogram of uranium. For a case-1 reactor, these costs were increased less than 2%. Barging was assumed impractical due to the conditions encountered on the West Coast.

Due to the large quantity of fuel to be shipped from the foreign reactor, it was considered practical to time-charter a vessel to ship the fuel to the U.S. The biggest problem with such overseas shipments is the procurement of adequate insurance. Some hull policies are voided if radioactive material is carried on board, and special insurance must be purchased. Assuming that such insurance were considered adequate, fuel shipped from Italy to Southern California via the port of New Orleans and then shipped by rail the rest of the way would cost $3.50 per kilogram of uranium. If the fuel were shipped by way of the Panama Canal with almost no overland transportation, transit time would increase 28%, but the unit cost would decrease to $1.25 per kilogram of uranium.

Domestic shipping costs of spent reactor fuels, under the conditions considered, are reasonable. Shipping costs from overseas ports to the U.S. can also be reasonable, particularly if the quantity of fuel is great enough to warrant time-chartering a vessel and if it can be transported with the involvement of very little land transportation.

INTRODUCTION

As a part of the program to study the economics of building large reactors for both water and power production, it is necessary to make reliable estimates of the fuel cycle costs, part of which are the charges incurred in shipping the spent fuel to a reprocessing site. This report presents, in a general way, the size and number of costs incurred in transporting spent fuel in the United States and from

overseas. Natural-uranium fuel is assumed. It is shown that shipping costs can be held to reasonable levels.

Ground rules specified that two natural uranium reactors be studied. The fuel elements for both reactors are identical. Pertinent reference design information for the reactors is as follows:

Reactor type	boiling water, pressure tube
Thermal power	
case 1	3,500 Mw
case 2	25,000 Mw
Burnup	8500 Mwd/metric ton of uranium
Load factor	90%
Fuel element form	2 concentric tubes of UO_2
Cladding	0.020-in.-thick Zircaloy-4
Outside dimensions	4.326 in. OD, 72 in. long
Uranium per element	112 kg of uranium
Specific power, av.	11.72 kw/kg of uranium

The first problem was to estimate the spent-fuel shipping costs both for the large and small reactors from an assumed site at Point Loma in Southern California to Hanford, Washington, for recovery of the uranium. The second problem was to estimate shipping costs for the large reactor from an assumed site in Italy to a hypothetical reprocessing plant in Southern California.

For maximum economy, a cask should carry as much radioactive material (payload) as possible. As the cask capacity increases, the ratio of cask weight to payload weight decreases, reducing the freight and handling costs per unit of payload. However, these considerations must be balanced against adequate safety and physical limitations such as crane capacities, floor loadings, the maximum gross weight adaptable to a particular form of transportation, etc.

Cost Sources

A number of railroads have subscribed to Docket 208, which sets forth the particular cost class under which spent fuel shipments may be made; this is discussed in more detail under the section on "Domestic Shipments" It is assumed that the classes set forth in Docket 208 could be obtained from any railroad for transporting spent fuel elements.

Much of the insurance information for both domestic and overseas shipments was gathered in telephone conversations with insurance representatives. The balance of the information was obtained from the open literature and in consultation with Mr. Sam Edlow of the Edlow Lead Co.

With respect to overseas shipments, many steamship companies will not now handle shipments of radioactive materials. Their feeling is that third-party liability insurance outside the U.S. is inadequate and in some cases[1] marine insurance is voided if radioactive materials are carried.

Freight rates for radioactive materials have been set in some conferences by the steamship companies.[2] However, it has been suggested[3] that the rates could be increased two or three times if forced circulation of coolant through the casks is required to keep the fuel-element temperatures acceptable. (Power failures with attendant stoppage of mechanical equipment are not uncommon on board ships.)

COST OF DOMESTIC SHIPMENTS

Shipping costs can normally be broken down into four categories:

1. freight charges,
2. depreciation charges on capital equipment,
3. handling charges, and
4. insurance charges.

Several of these charges are discussed in more detail below.

Freight Charges

Domestic rail-freight charges for spent fuel elements have been put forth by a number of railroads in Docket 208. Under its provisions, spent fuel elements may be shipped in carload lots (40,000 lb, minimum) with a released value of $0.40 a pound as class 40 (40% of the first class rate), with a released value of $1.00 a pound as class 70, and with a released value of $5.00 a pound as class 85. The released value is the rate at which the shipper will be paid in case of loss by the railroad. Shipments by the government are normally dispatched at the lowest valuation, in this case, class 40. The returning empties will probably be shipped as class 37-1/2.

Railroads are not as easy to negotiate rates with as trucking firms. Rates for shipping radioactive material by truck have been negotiated in the range of $0.60 a mile under Section 22, which is a government bill of lading.[8] Oak Ridge Operations Office felt that similar rates could probably be negotiated for any shipper wishing to transport spent fuel elements by truck to a fuel recovery site on a continuing basis.

Handling Charges

Handling charges arise from the loading and unloading of the casks. In addition, decontamination costs may be included in this category. Reasonable costs for decontamination might be $50 per man-day.

Insurance Charges

Many facilities have been indemnified pursuant to the Price-Anderson Act under which the facilities' public liability is guarantied above their purchased insurance by the government, to an aggregate sum of $500,000,000. This insurance covers transportation of radioactive materials to and from the fuel recovery plant. In addition, persons who engage in shipping of radioactive material may, if they wish, purchase additional third-party protection up to $60,000,000 from a nuclear pool under a Suppliers and Transporters Form. Annual premiums for this latter coverage are $750 for the first million dollars of coverage, $375 per million for the next $9 million of coverage, and $250 for each additional million of coverage up to $60 million.[4]

COST OF OVERSEAS SHIPMENTS

Freight Costs

Freight charges for spent fuel elements carried by a Pacific Coast European Conference ship from the West Coast to Italy have been quoted at $186.50 per 2000 lb.[2] However, the cost of shipping spent fuel from Italy to the West Coast is about $600 per 2000 lb.[3] This latter cost will probably be reduced at some future time to more closely match the outbound charges.

In addition to the normal ocean freight charges on radioactive materials there are wharfage fees, which could run as high as $1.00 a ton, loading and unloading fees, including heavy lift charges (a heavy-lift

barge might be rented for $100 an hour) and port charges. There is also the probable extra hazards pay required by the stevedores for loading and unloading dangerous cargo. To these costs must be added surface transportation charges in the United States and Europe.

The bulk of the charges noted above are for the ocean trip. If there is enough spent fuel available for shipment to warrant it, a vessel could be time chartered for a specified length of time for the express purpose of transporting spent fuel.

Such a time charter of a Liberty ship could be made for about $21,000 a month on a year's charter, plus the cost of fueling the ship. A Liberty ship uses 180 bbl of oil a day at sea and 50 bbl a day in port. The cost of fuel oil depends upon where the ship bunkers but may be estimated at about $2.80 a barrel. In addition, penalty wages for the crew may be incurred for handling dangerous cargo.

If such continuous shipments were to be made over an extended period of time, it would probably be useful to establish a budget of about $70,000 a year for three people to handle all the office work and to expedite the shipments. This budget includes travel expenses to and from Europe several times a year.

Very thorough cask inspections by port authorities and Health Physics personnel will have to be made upon loading and unloading the cargo. The cost per shipment may be estimated at $10,000 in Europe, $10,000 in the U.S. which includes all the equipment necessary for the inspections.

Equipment Costs

For large-scale overseas shipments, a considerable amount of money would be tied up in capital equipment such as casks. The casks should be kept to a moderate size due to the floor-loading limit posed by most cargo ships, which ranges from 850 to 1000 lb/ft^2 and can be increased only by reinforcing the decks and hull. Large load-spreading bases can be used, but these can become cumbersome. In addition, it is not a good idea to increase the load of spent fuel in the cask to the extent that pumps are needed to provide forced-circulation coolant to remove the decay heat from the spent elements. Mechanical equipment is quite vulnerable to loss of electrical power on board ship.

As a first approximation, a steel-shelled, lead-filled shipping cask may be costed at $1.00 a pound. Unless the cask is quite complex, this price can probably be reduced to half this value, particularly, if a large number is ordered.

The number of casks needed will depend on the round-trip shipping time of the casks from the reactor site to the reprocessing site. For example, assuming that each cask can hold a half-day supply of discharged fuel elements and that the round-trip time is 50 days, a minimum of 100 casks would have to be built to ensure no net accumulation of spent fuel at the reactor site.

Insurance Costs

The problem of insurance covering radioactive shipments overseas is one of great concern. Due to the lack of adequate insurance, there have been very few shipments overseas, and there has been a lack of adequate insurance because of the slight experience on which an insurance company can base its rates. Indeed, some insurors void their normal hull and cargo insurance if radioactive material is carried on board.

Marine insurance (covering hull and cargo) which has been purchased from a U.S. firm presently has no nuclear exclusion clause. This means that the normal insurance policy covers the hull and companion cargo if radioactive damage is sustained. However, this is not true of marine insurance purchased in foreign markets. Therefore, additional coverage must be purchased and may be obtained from foreign firms for as low as 0.24% of the declared value.

As regards third-party liability, shipments entering the continental United States (inside the three-mile limit) are indemnified to the extent of $500,000,000 by the U.S. Government if the fuel is going to a nuclear facility, such as fuel recovery plant. For shipments outside the continental United States, insurance may be purchased up to $15,000,000 from two U.S. nuclear insurance pools.[5] These are the Nuclear Energy Liability Insurance Association (NELIA) and the Mutual Atomic Energy Liability Underwriters (MAELU). NELIA will provide $10,000,000 of the total insurance, with MAELU assuming about $5,000,000.

In discussing the availability of this insurance with F. X. Boylan, Assistant General Manager of NELIA, he felt that the position of his

company was that it was interested in accommodating American interests doing business overseas but that the company was not trying to sell such insurance to foreign interests at this time. The insurance could be purchased for $1500 for the first million, $750 per million for the next 4 million, and $500 per million for the remaining 5 million dollars. This insurance is on a per-trip basis and is not a function of the amount of material shipped.

There are also foreign markets from which third-party liability may be purchased.[3] It is limited to $14,000,000, and the premium is $3,500 per shipment, considerably cheaper than it can be purchased in the United States. Insurance is thus available. The only problem is convincing steamship owners and operators that it is enough insurance. (They usually have visions of contaminating New York Harbor.) The few shipments that the United Kingdom has made were indemnified by the government.[6]

The Organization for Economic Cooperation of European States (OEEC) has signed a convention by 17 nations,[7] which contains provisions covering shipment of nuclear materials by the member states. At present, the limits of liability are $5,000,000 to $15,000,000. A supplemental convention known as the Euratom Convention has proposed to supplement this indemnity to between $70,000,000 and $120,000,000. To date, neither convention has been ratified, but steps are being taken to alleviate this problem of obtaining sufficient insurance.

SHIPPING COSTS FROM POINT LOMA, CALIFORNIA, TO HANFORD, WASHINGTON

In order to use the previously specified information to predict shipping costs from Point Loma to Hanford, the following assumptions were made.

1. The cask would conform to the proposed Federal regulations, the most stringent of which, for this study, were the temperature limitations placed on the fuel elements.

2. All shipments would be insured under the Price-Anderson Act which covers third-party liability inside the United States.

3. The casks would be owned by the reactor operator and depreciated at 7.7% per year.

4. Casks would cost $1 a pound since a limited number would be required.

5. Handling of the casks would cost $500 per cask round trip.

6. Docket 208 would govern the freight rates.

7. Truck transportation could handle a 13-element cask (49,000 lb, loaded) and rail could handle either a 13-element cask, a 26-element cask (87,800 lb, loaded), or a 48-element cask (150,300 lb, loaded). The largest cask is borderline with respect to keeping the temperatures of the center elements below the temperature noted in assumption 8, below.

8. The maximum temperature that the elements could be allowed to reach under dry-air conditions inside the cask would be about 650°F (since it has been experimentally verified that Zircaloy-clad fuel elements can maintain their integrity for an extended period of time at temperatures ranging between 800 and 900°F, the temperature of the fuel would therefore be allowed to rise to within 200°F of this experimentally determined safe temperature in case the cooling water were lost.)

9. The cask shielding would be designed to maintain the external dose rate at 10 mr/hr at 1 m.

10. Two reactors are considered, case 1 and case 2; case 1 (at 3500 Mw) discharges 0.5 ton of fuel per day (4.5 elements) and case 2 (at 25,000 Mw) discharges 3.0 tons of fuel per day (26.7 elements).

Costs for Shipping by Truck

It has been assumed that casks which weigh 49,000 lb, loaded can be transported over roads from California to Hanford. Other assumptions concerning truck shipments are listed below.

Assumptions

One-way distance = 1176 miles

Assume shipping cost of $0.57/mile; time per round-trip = 6 days[8]

Freight Costs

Freight costs = ($0.57)(2 ways)(1176) = $1,340.64

Unit cost = $1,340.64/(13 elements)(112 kg U) = $0.92 kg U

Depreciation Costs

	For Reactor Discharge of 0.5 ton/day (case 1)	For Reactor Discharge of 3.0 ton/day (case 2)
No. of casks necessary	3	~14
Weight of empty cask, lb	45,100	45,100
Cost of casks at $1/lb	$135,300	$633,000
Depreciation at 7.7%/yr	$10,400	$48,700
Cost, $/kg U	$0.06	$0.04

Handling Costs

	For Reactor Discharge of 0.5 ton/day(case 1)	For Reactor Discharge of 3.0 ton/day(case 2)
No. of trips per year	124	738
Yearly handling cost at $500/trip	$62,000	$369,000
Handling cost, $/kg U	$0.34	$0.34

The total cost, assuming that third-party liability insurance coverage is provided by the reprocessing facility or reactor facility is $1.32 per kilogram of uranium for the 0.5 ton/day reactor and $1.30 per kilogram of uranium for the 3.0 ton/day reactor.

Costs for Shipping by Rail

The first-class rate from Point Loma (San Diego), California, to Hanford, Washington, is $7.14 per hundredweight. Assuming a released value of $0.40 per pound, the shipment will go under class 40. The round trip by rail is assumed to take 12 days, and the breakdown of the costs is given below.

Freight Costs

The freight costs are listed below for shipping 13-, 26-, and 48-element casks round-trip by rail.

13-Element Cask

Loaded: (49,000 lb/100 lb)($7.14)(0.40) = $1,400

Empty: (45,100 lb/100 lb)($7.14)(0.375) = $1,210

$2,610 per trip

Cost: $\frac{\$2,610}{(13 \text{ elements})(112 \text{ kg/element})}$ = $1.80 per kg of U

26-Element Cask

Loaded: (87,800 lb/100 lb)($2.86/cwt) = $2,520

Empty: (80,000 lb/100 lb)($2.68/cwt) = $2,150

$4,670 per trip

Cost: $\frac{\$4,670}{(26 \text{ elements})(112 \text{ kg/element})}$ = $1.60 per kg of U

48-Element Cask

Loaded: (150,300 lb/100 lb)($2.86/cwt) = $4,300

Empty: (135,900 lb/100 lb)($2.68/cwt) = $3,640

$7,940 per trip

Cost: $\frac{\$7,940}{(48 \text{ elements})(112 \text{ kg U/element})}$ = $1.48 per kg of U

Depreciation Costs

The depreciation costs for the three size casks used in servicing the case 1 and case 2 reactors are shown in Tables 1 and 2, respectively.

Table 1. Case 1, Reactor Discharge, 0.5 ton/day

Elements/Cask	Weight (lb)	Casks Req'd	Cost ($)	Depreciation ($/yr)	Cost ($/kg U)
13	45,100	6	270,600	20,800	0.11
26	80,000	3	240,000	18,400	0.10
48	135,900	2	271,800	20,900	0.11

Table 2. Case 2, Reactor Discharge, 3.0 tons/day

Elements/Cask	Weight (lb)	Casks Req'd	Cost ($)	Depreciation ($/yr)	Cost ($/kg U)
13	45,100	28	1,262,000	97,200	0.09
26	80,000	15	1,200,000	92,400	0.09
48	135,900	10	1,359,000	104,600	0.10

Handling Costs

The cask handling costs for case 1 and case 2 reactors assuming $500 per round-trip are given in Tables 3 and 4, respectively.

Table 3. Case 1, Reactor Discharge, 0.5 ton/day

Elements/Cask	Trips/yr	Cost/yr	Cost ($/kg U)
13	124	62,000	0.34
26	62	31,000	0.17
48	34	17,000	0.10

Table 4. Case 2, Reactor Discharge, 3.0 tons/day

Elements/Cask	Trips/yr	Cost/yr	Cost ($/kg U)
13	740	370,000	0.34
26	370	185,000	0.17
48	200	100,000	0.09

(The total shipping charges for the spent fuel are shown in Table 5, and it is assumed that insurance coverage is provided by the railroad and the facility.)

Costs for Shipping by Barge

Barge rates for transportation along the West Coast on a charter basis are as follows:[8]

Cost of tug	$1000/day
Cost of 4000-8000-ton barge	200/day
	$1200/day of use

The standby charge for loading and unloading is $700 a day. It is estimated that under normal conditions the running time from Point Loma to Hanford would be ten days each direction, assuming that in a few years such heavy barges will be capable of traveling all the way up to the Columbia River to Hanford. If the barge could be used on a continuing basis, the use charge of $1200 a day could be cut in half.

These barge rates could produce the lowest shipping charges of all means considered if schedules could be met. For case 2, costs could be as low as $0.43 per kilogram of uranium. However, there is the disadvantage, particularly on the West Coast, that shipments are affected to a great extent by weather. There is no inland waterway, and schedules are not dependable, which accounts for the little barge traffic that exists there now. In addition, the Price-Anderson indemnification act is void outside the three-mile limit, a situation which could be costly should the barge be swept out to sea and wrecked.

Summary of Comparative Costs for Truck and Rail Shipments

The cost of transporting spent fuel elements from case 1 and case 2 reactors situated at Point Loma to Hanford is consolidated in Table 5. The costs include freight, handling, and depreciation charges. Insurance coverage should be supplied by the originating facility. If desired, additional liability insurance in the amount of $50 million could be purchased by the transporter at a cost of less than $0.08 per kilogram of uranium shipped based on the 0.5-ton/day reactor, and $0.013 per kilogram of uranium shipped based on the 3.0-ton/day reactor.

Table 5. Comparison of Round-Trip Shipping Costs of Spent Reactor Fuel from Point Loma, Calif., to Hanford, Wash.

	Type of Transportation			
	Truck	Rail		
Round-trip time, days	6	12	12	12
No. of elements/cask	13	13	26	48
Cost, $/kg U (case 1)	1.32	2.25	1.87	1.69
Cost, $/kg U (case 2)	1.30	2.23	1.86	1.67

It is evident from Table 5 that, other things being equal, for rail shipments it is desirable to use as large a cask as possible (certainly consideration will have to be given to problems of heat transfer, etc., which are not covered at this point). It also appears that truck transportation may be somewhat cheaper than rail, though

possible additional fees incurred from overweight loads would cause some increase in this figure. Even though there does not appear to be much price competition between truck and rail for the cask which carried 13 spent elements, safety must be considered before a mode of transportation is chosen.

OVERSEAS SHIPPING COSTS: ITALY TO SOUTHERN CALIFORNIA VIA A GULF COAST PORT

Assume that a large, 25,000-Mw reactor is built in northern Italy on the seacoast, having its own pier facilities. The reactor discharges 3 tons of fuel per day. The shipments are to be made to a reprocessing site in southern California, near San Diego. The casks are designed to carry 13 elements each (about a 1/2-days' discharge from the reactor) and weigh around 49,000 lb, loaded. Assume also that these elements should not be shipped through the Panama Canal to the West Coast but to New Orleans, off-loaded onto waiting flatcars and transported by rail to San Diego.

Cost Assumptions

Since this is a continuing operation, a Liberty ship is time-chartered for several years to carry the spent elements. In order to determine the operating cost of the ship, the following assumptions were made:

Cask loading on board ship	=	2 days
Speed of Liberty ship	=	10 knots
Distance from Italy to New Orleans	=	5500 nautical miles
Time of one-way trip $= \frac{5500 \text{ naut. miles}}{(10 \text{ knots/hr})(24 \text{ hr/day})}$	$\cong$	23 days
Time for off-loading cargo in New Orleans	=	2 days
Time of one-way trip for a special train from New Orleans to San Diego $= \frac{1830 \text{ miles}}{(\sim 350 \text{ miles/day})}$	$\cong$	5 days
Time for unloading fuel at reprocessing site	=	4 days

Round-Trip Time

Operation	Time (Days)
Cask loading	2
Round-trip by ship	46
Off-loading at New Orleans	2
Round-trip from New Orleans to San Diego	10
Unloading fuel at reprocessing site	4
On-loading empty casks in New Orleans	2
Off-loading empty casks in Italy	2
Total days required	68

Total Charges in Port

$$\text{Minimum number of casks needed} = \frac{68 \text{ days}}{\text{1/2 day fuel per cask}} = 136 \text{ casks}$$

Casks built = 164 (2 weeks extra of fuel discharge)

$$\text{Cost of chartered ship per trip} = \frac{68}{30} (\$21{,}000/\text{month}) = \$47{,}500$$

Cost of fuel

At sea:	(180 bbl/day)($2.80/bbl)(46 days)	= $23,200	
In port:	(50 bbl/day)($2.80/bbl)(22 days)	= $ 3,100	
		$73,800	$73,800

Each cask weights 45,100 lb
Weight of fuel 3,900 lb
49,000 lb/cask = 22.3 metric tons

Total weight carried on board ship (not including tiedowns) =
(136 casks)(22.3 metric tons/cask) = 3030 metric tons

Loading and unloading (both ports)	$4/ton
Wharfage (both ports)	$4/ton
Port charges	$8/ton
	$16/ton

($16/ton)(3030 metric tons) = $48,500 $48,500

Inspection and Expediting Costs

Inspection and cask testing by Health Physics and Port Authorities in Europe and US = $20,000

With a budget of $70,000 a year for office work and expediting, this cost will be: $70,000/year/5.4 trips/year = $13,000

Transportation Charges in United States

First-class fare from New Orleans to San Diego = $9/cwt
Distance from New Orleans to San Diego = 1839 miles
Assume 2 casks per rail car; thus 68 cars will be needed.
Since elements will be shipped full as class 40, empty as class 37-1/2, the cost will be:

$$(\$9/\text{cwt})(0.40)\ \frac{98{,}000\ \text{lb}}{100\ \text{lb}}\ (68\ \text{cars}) = \$240{,}000$$

The cost of returning the empties will be:

$$(\$9/\text{cwt})(0.375)\ \frac{98{,}000\ \text{lb}}{100\ \text{lb}}\ (68\ \text{cars}) = \$224{,}000$$

Total $464,000 $464,000

Equipment Costs

The number of trips per year will be:

$$\frac{365\ \text{days/year}}{68\ \text{days/trip}} = 5.4\ \text{trips per year}$$

Equipment Depreciation for 164 Casks at 7.7%/year

Assume that with this large order and simple design the cost is $0.50/lb.

Cost of casks = (45,100 lb/cask)($0.50/lb)(164 casks) =

$3,700,000

$$\text{Depreciation per trip} = (\$3{,}700{,}000)(0.077)\left(\frac{1}{5.4\ \text{trips/yr}}\right) = \$\ 52{,}800$$

Insurance Costs

Value of the cargo: Assume that each element is worth approximately $2,700.

Total worth of spent fuel =
($2700/element)(13 elements/cask)(136 casks/ship) = $4,800,000

Cask worth = $\frac{136}{164}$ ($3,700,000) = $3,070,000

Total worth $7,870,000

Loss insurance at 0.24% of value of material shipped =
(0.0024)($7,870,000) = $18,600

Liability insurance on ship ($14,000,000 maximum) 3,500
(Coverage in United States is provided by the indemnified reprocessing facility. Loss insurance is provided by the railroad to $0.40/lb. In case of accident, the material could still be recovered.)

Total cost per trip = $694,200

Unit Cost

The number of kilograms of uranium for the total load =
(13 elements/cask)(136 casks)(112 kg U/element) = 198,000 kg uranium

The unit cost per kilogram of uranium = $\frac{\$694,200}{198,000 \text{ kg U}}$ = $3.50

OVERSEAS SHIPPING COSTS FROM ITALY TO SOUTHERN CALIFORNIA VIA THE PANAMA CANAL

It is interesting to compare the above costs with those for shipping the spent fuel directly to Southern California through the Panama Canal (which probably will be allowed).[3] The shipping charges are the same as those for the trip via a Gulf Coast port.

The in-transit time is longer than for the previous case, which results in a need for more casks per trip and thus greater capital investment. The time analysis is given below.

Assumptions

Time required to load casks on board ship	3 days
Distance from Italy to Southern California	~ 8200 naut. mi.

$$\text{Time of one-way trip} = \frac{8200 \text{ naut. miles}}{(10 \text{ knots/hr})(24 \text{ hr/day})} \cong 34 \text{ days}$$

Off-loading in California	3 days
Time for trip to reprocessing plant	1/2 day
Time for fuel at reprocessing site	6 days

Total Time

Operation	Time (days)
Cask loading (Italy)	3
Round-trip by ship	68
Off and on loading in California	6
Trip to and from reprocessing site	1
Unloading fuel at reprocessing site	6
Cask unloading (Italy)	3
Total days required	87

Freight Costs

$$\text{Minimum no. of casks needed} = \frac{87 \text{ days}}{\text{1/2-day fuel per cask}} = 174 \text{ casks}$$

No. of casks built = 200 (two extra weeks discharge)

$$\text{Cost of chartered ship per trip} = \frac{87}{30} (\$21{,}000/\text{month}) = \$61{,}000$$

Cost of Fuel

At sea: (180 bbl day)($2.80/bbl)(68 days) =	$34,300	
In port: (50 bbl/day)($2.80/bbl)(19 days) =	$ 2,700	
	$37,000	$37,000

Total Charges in Port

Cask weight loaded = 22.3 metric tons

Total weight carried (not including tiedowns) =
(174 casks)(22.3 metric ton/cask) = 3880 metric ton

Cost of port, warfage, loading, etc.) = $16/metric ton

Cost per trip = ($16/metric ton)(3880 metric ton) = $62,000

Cost of passing two ways through the Panama Canal = $10,000

Equipment Costs

Equipment depreciation for 200 casks at 7.7%/yr

Assume that with this large order and simple design
the cost is $0.50/lb

Therefore, the cost of casks is:
(45,100 lb/cask)($0.50/lb)(200 casks) = $4,510,000

Depreciation per trip = $($4,510,000)(0.077) $\frac{87 \text{ days/trip}}{365 \text{ days/year}}$ = $82,800

Inspection and Expediting Cost

There are $\frac{365 \text{ days/year}}{87 \text{ days/trip}}$ = 4.2 trips/year

With a budget of $70,000 per year for paper work and expediting,

the unit cost is: $\frac{\$70,000/\text{year}}{4.2 \text{ trips/year}}$ = $16,700

Inspection and cask testing by Health Physics and Port Authorities
in Europe and US is $20,000 per trip $20,000

Insurance Costs

Value of cargo: Each element is worth about $2,700.

Total worth of spent fuel is:

($2,700)(13 elements/cask)(174 casks/ship) = $6,100,000

Cask worth = $\frac{174}{200}$ ($4,510,000) = $3,930,000

$10,030,000

Cost of loss insurance at 0.24% of value of material shipped =
(0.0024)($10,030,000) = $24,000

Cost of liability insurance on ship ($14,000,000 maximum) = 3,500

Total cost per trip = $317,000

The number of kilograms of uranium for the total load =
(13 elements/cask)(174 casks)(112 kg U per element) =
253,000 kilograms of uranium

The unit cost per kilogram of uranium = $\frac{\$317,000/\text{trip}}{253,000 \text{ kg U/trip}}$ = $1.25

It is evident that land transportation is much more expensive than sea transportation when a large volume of material has to be moved on a continuing basis and that advantage can be taken of time-chartering a ship.

CONCLUSIONS

This paper presents a generalized picture of the magnitude and number of costs incurred in transporting spent fuel both in the United States and from overseas which has been discharged from large natural uranium reactors. It is evident that for this type of system, shipping costs can be kept at quite reasonable values.

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