Advanced Fuel Cycle Cost Basis Report: O Modules Transportation Processes

Nuclear Fuel Cycle and Supply Chain

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ACKNOWLEDGEMENT

This latest version of the Module O Transportation Process is the result of the cumulative effort of many authors that have contributed to the Advanced Fuel Cycle Cost Basis Report (AFC-CBR). It is not possible to identify and acknowledge all those contributions to the AFC-CBR and this module. All the authors, including the four primary authors, fifteen contributing authors, the twelve contributors acknowledged, and the many other unacknowledged contributors in the 2017 version of the report may have contributed various amounts to the development and writing of this module prior to this current revision. Unfortunately, there is not a consolidated history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

This update reformats previous work to the current format for rerelease of the entire report as individual modules so there is no primary technical developer or lead author. J. Hansen (INL) and E. Hoffman (ANL) can be contacted with any questions regarding this document.

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ACRONYMS

AFC	Advanced Fuel Cycle
BWR	boiling water reactor
CPI	Consumer Price Index
DOE	U.S. Department of Energy
DOT	Department of Transportation
DUF_6	depleted UF_6
DUO_2	depleted UO_2
EUF_6	enriched UF_6
GNEP	Global Nuclear Energy Partnership
GTCC	greater than Class C
HLW	high-level waste
MOX	Mixed oxide fuel
MTHM	metric tons of heavy metal
MTIHM	metric tons of initial heavy metal
NOAK	n^{th} of a kind
NRC	Nuclear Regulatory Commission
O&M	Operations and Maintenance
PWR	pressurized water reactor
SNF	Spent nuclear fuel
TRU	transuranic
UFD	Used Fuel Disposition
UNF	used nuclear fuel
WIT	What-It-Takes
YMP	Yucca Mountain Project

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Module O1

Transportation of Radioactive Materials

O1 REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2004	O1-All	**Version of AFC-CBR in which Module first appeared:** 2004 as Module N, which included data on fabricated fuel transportation which was later covered on Module O2. (In 2006 it was decided to include this Module O1 in a two-part Module O. SNF and HLW transportation became Module O1 and other less radioactive material transport as Module O2) Up to 2012 transportation cost estimates were based on shipping SNF and packaged HLW directly to Yucca Mountain. Models developed at Sandia National Laboratory and Oak Ridge National Laboratory were used for cost estimate development (Johnson, et al 2003 and Michelhaugh 2002).
	2012	O1-All	**Version of module in which new technical data was used to establish "what-it-takes" unit cost ranges:** 2015 • 2012 UFD Campaign transportation cost data (from Systems Architecture Study) was reported for the first time in the 2015 AFC-CBR. It was escalated to 2017$ for this latest revision (9% increase in unit cost from 2012 to 2017).
	2015	O1-All	**New technical/cost data which has recently become available and will benefit next revision:** • Since 2015 the DOE-NE UFD Campaign and its contractors have prepared several reports comparing the costs of Government-financed at-reactor dry cask SNF storage and subsequent geologic repository disposal to the construction and operation of an Interim Storage Facility (ISF) followed by geologic repository disposal. Transportation costs were major parts of these studies. • Since 2015 it has been decided that a separate geologic repository is needed for HLW arising from DOE's defense operations. Reposts on the projected costs, including cask transportation for this facility, may be available.
	2021	All	Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from year of technical basis to escalated year 2020. Cost estimates are in US dollars ($) of year 2020.

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Module O1

TRANSPORTATION OF RADIOACTIVE MATERIALS

O1-MD. SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year 2020 for this FY21 update.**
- **Nature of this FY21 Module update from previous AFC-CBRs:** Escalation only
- **Estimating Methodology for latest technical update from which this FY21 update was escalated:** For SNF and HLW transportation cost data is developed from Life Cycle Cost Assessments prepared by DOE-NE's Used Fuel Disposition (UFD) campaign as part of a 2012 Systems Architecture Study. Bottom-up estimates were prepared for shipment to a generic Central Storage Facility and ultimately to a generic Geologic Repository.

O1-1. BASIC INFORMATION

This module develops cost estimates for the shipment of:

- Spent nuclear fuel (SNF) from nuclear power plants to a monitored retrieval storage facility, to a permanent geologic repository, or to other disposal or processing facilities. SNF is assumed to be intact fuel rods in assemblies or bundles placed into a canister. Damaged fuel will be packed into an additional container in such a manner as to prevent criticality or contamination.
- Vitrified high-level waste (HLW) from vitrification plants to a monitored retrieval storage facility, to a permanent geologic repository, or to other disposal facilities. HLW is assumed to be in a glass form (presumably a borosilicate glass) and placed in canisters.
- Mixed oxide fuel (MOX)[a] from MOX fuel fabrication facilities to nuclear power plants. MOX is assumed to be intact fuel rods in assemblies placed into canisters.
- Fuel from naval reactor cores could be handled in a manner similar to that described herein. However, some details of naval fuel remain classified. Recovery of residual fuel values or disposal is the responsibility of the federal government and is not included in this study.

Spent nuclear fuel and vitrified HLW are shipped in shielded casks that are licensed by the Nuclear Regulatory Commission (NRC) and meet NRC requirements for Type-B packages per 10 CFR 73 (NRC 2009). In this module, it is assumed that MOX will be shipped in Type-B packages.

The Type-B packages[b] that are used to ship SNF, MOX, and vitrified HLW use massive, highly shielded casks that are fitted on their ends with energy absorbing devices called impact limiters, which protect the cask and its bolted closure from damage during high speed impact accidents. The highly radioactive materials that are shipped in Type-B packages may be placed in a metal canister that has a lid that is welded to its body before they are loaded into the Type-B package. Vitrified HLW is always canisterized before it is shipped in a Type-B package. Although some Type-B package systems for SNF

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[a] MOX often refers to fuel containing a mix of oxides of uranium and of plutonium that is primarily Pu-239. The term "TRUMOX" is used to describe fuels containing other transuranic nuclides or greater concentrations of the higher plutonium isotopes. In this section, MOX refers to both of these fuels.

[b] In this section, the term "packaging" refers to the devices into which radioactive material is placed for shipment—in other words, the shipping container. The term "package" refers to the container and its contents.

and MOX do not use canisters, it is assumed in this module that both SNF and MOX are canisterized when shipped in Type-B packages. Because of the length of the MOX assemblies, the shipping casks will be similar to, if not the same as, the casks used for SNF.

Transportation costs for materials shipped as Type-B packages consist of the cost of the Type-B packaging, loading costs at the shipment origin, shipping costs while in transit, and unloading costs at the shipment destination. The transportation costs developed in this module assume that the Type-B packaging is a HI-STAR cask. The HI-STAR cask system was selected as the basis for packaging costing because of the quantity of detailed information available. Its selection makes no statement regarding the merits of other cask systems. Rudimentary investigation indicates that all modern commercial Type-B cask systems approved by the NRC for the shipment of SNF, MOX, and vitrified HLW are cost competitive based on life-cycle cost estimates.

O1-2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

The HI-STAR cask system consists of (a) a multipurpose canister equipped with a welded lid that contains the spent fuel assemblies, (b) an overpack in which the canister is housed that provides the required radiation shielding, and (c) two impact limiters, which, when mounted on the ends of the overpack, protect the overpack from the mechanical loads that the cask system might experience during severe collision accidents. Figure O1-2 shows these three principal components of the HI-STAR cask system.

Because the overpack and the two impact limiters can be reused, the cost calculations presented below amortize the costs of these cask system components over the useful life of these components. Because the multipurpose canister is a single use item, its cost is a one-time expense. Since failure of rod cladding due to embrittlement is not a significant concern for average burnup spent fuel, the multipurpose canister may be used to house spent fuel when stored in a geologic repository. If so used, its lifetime should essentially be the same as the lifetime of the geologic repository.

It is possible that the shattering of embrittled high burnup spent fuel cladding might cause a critical pile of spent fuel pellets to form in the bottom of the multipurpose canister before emplacement in a permanent repository. Consequently, transfer of high burnup spent fuel assemblies from the multipurpose canister to single assembly canisters could be required to prevent a criticality event. Such transfer of high burnup assemblies to single assembly canisters is not treated by this module, and the associated cost does not affect the cost estimates developed here.

NRC cask licenses must be renewed every 5 years. In theory, there is no limit on the number of times a cask license can be renewed. However, technological advances tend to render casks obsolete after 20 to 30 years. Moreover, licenses are often revised at less than 5-year intervals because of ongoing changes to the cask design or operational envelope.

Although SNF, MOX, and vitrified HLW can be shipped by truck or by rail, the majority of future shipments of these materials are expected to be by rail. Therefore, only rail casks are considered in this module. Table O1-1 presents SNF capacities for five typical SNF rail casks. The information in Table O1-1 was extracted from the cask Safety Analysis Report for Packaging that the cask manufacturer submitted to the NRC in support of the cask's license application. Because SNF transportation cask systems and in particular the HI-STAR transportation cask system are commercially available technology, the quality of the cost data presented in Table O1-1 is entirely adequate for the scoping analyses performed in this module.

Module G states that the outside diameter of vitrified HLW canisters is 2 ft. Because the inside diameter of the HI-STAR cask cavity is 69-3/4 in., a HI-STAR cask licensed to carry vitrified HLW should be able to carry six vitrified HLW canisters (five canisters placed in a pentagonal array positioned around one central canister) after meeting cask thermal limits by cooling of the vitrified HLW.

Table O1-1 shows that, regardless of fuel type (pressurized water reactor [PWR] or boiling water reactor [BWR]) most SNF Type-B casks can transport about 10 metric tons of initial heavy metal (MTIHM). Thus, for both SNF and for MOX, the shipment packaging cost per kg of initial heavy metal (uranium and plutonium) roughly equals the cask system cost divided by 10^4.

Table O1-1. Cask capacities.

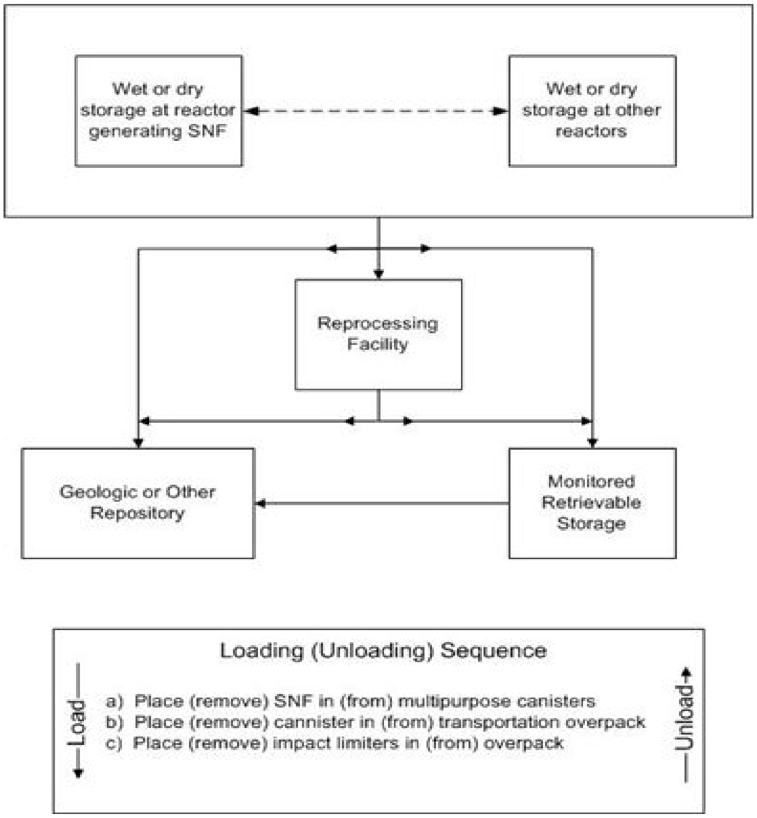
	Pressurized Water Reactor Fuel Assembly Design			Boiling Water Reactor Fuel Assembly		
Cask	Ass'y per Cask	Initial U kg/Ass'y	Initial U kg/Cask	Ass'y per Cask	Initial U kg/Ass'y	Initial U kg/Cask
HI-STAR 100	24	440	10,560	68	150	10,200
BFS-TS125	24	440	10,560			
NAC-UMS	24	440	10,560	64	150	9,600
NAC-STC	26	440	11,440	56	180	10,080

O1-3. PICTURES AND DIAGRAMS

The block diagram in Figure O1-1 presents a flow chart for the operational steps that support the loading of SNF into an SNF cask at a nuclear reactor and shipment of the SNF to a reprocessing plant, a permanent storage facility (e.g., Yucca Mountain Project [YMP]), or an interim storage facility (e.g., PFS, or possibly a spent fuel pool or dry storage facility located at another nuclear reactor).

The diagram shows that the SNF loading sequence consists of three steps. First, the SNF assemblies are loaded into a multipurpose canister; second, the canister is placed in a transportation cask overpack; and finally, the overpack is equipped with impact limiters. After shipment to a reprocessing or storage facility, the multipurpose canister is removed from the cask overpack by reversing the loading sequence, after which the overpack and its impact limiters can be reused.

The functional block diagram for vitrified HLW packaging and transportation would be identical to Figure O1-1 with the topmost block in the diagram that represents storage of SNF at reactor sites replaced by a block that represents storage of vitrified HLW in canisters at the vitrification facility. The functional block diagram for MOX would be very simple, as it would consist of only two blocks, one for the MOX fabrication facility and one for the nuclear power plant to which the MOX fuel is shipped.

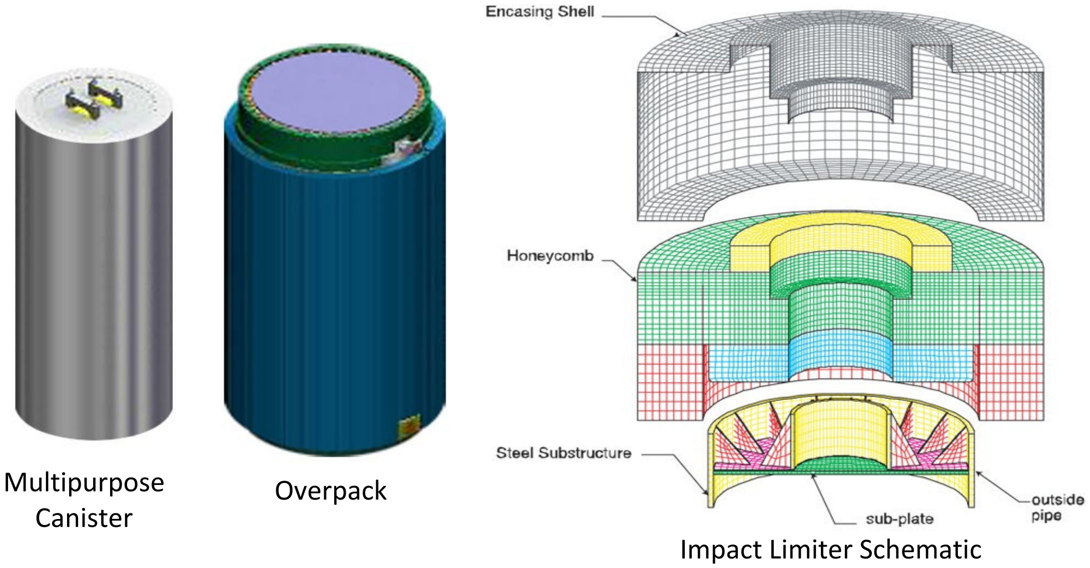


Loading (Unloading) Sequence

a) Place (remove) SNF in (from) multipurpose canisters
b) Place (remove) cannister in (from) transportation overpack
c) Place (remove) impact limiters in (from) overpack

Figure O1-1. Functional block diagram for SNF packaging and transportation.

Figure O1-2 shows the HI-STAR cask canister and transportation overpack and a schematic of one of the two transportation overpack impact limiters.



Multipurpose Canister

Overpack

Impact Limiter Schematic

Figure O1-2. HI-STAR cask components.

O1-4. MODULE INTERFACES

Module O receives vitrified HLW from vitrification plants (Module G) and SNF from interim storage in spent fuel pools or dry storage facilities at nuclear power plants (Modules E1 and E2). After packaging, Module O delivers them to interim storage facilities at another nuclear power plant (Modules E1 and E2), to long-term monitored retrieval storage facilities (Module I), or to geologic repositories (Module L). Module O also receives MOX fuel from recycled fuel fabrication plants (Module F2/D2) and delivers this recycled fuel to nuclear power plants.

O1-5. SCALING CONSIDERATIONS

The analysis presented below show that the cost of shipping a single SNF or MOX cask by dedicated train will depend principally on the cost of the single-use canister that houses the SNF or the MOX. Thus, for a single shipment of one cask, shipping costs will be relatively invariant. Of course, the cost of a single shipment should scale more-or-less linearly with the number of casks in the shipment. In addition, the annual shipping costs for SNF and MOX should approximately equal the product of the annual cost per operating reactor and the number of operating reactors. For vitrified HLW, since canister costs are an operating expense for the vitrification facility, shipping costs per cask depend principally on en-route shipping costs per cask and thus should also scale with the number of casks per shipment and with the number of operating reactors.

O1-6. COST BASES, ASSUMPTIONS AND DATA SOURCES

Annex OX to this module derives the algorithm used to estimate transportation costs under consideration for this module and for Module O2 Costs that are not package-specific are provided there, including costs that have been input to a Monte Carlo analysis as distributions.

O1-6.1 PACKAGING COSTS

The costs developed for this module assume that, after placed or poured into a single-use canister, SNF, MOX, and vitrified HLW are shipped in reusable Type-B packagings that are equipped with reusable impact limiters. Although these highly radioactive materials can be shipped in either truck or rail casks, the costs developed in this module assume shipment in rail casks.

In 2001, Sandia National Laboratories solicited informal quotes for several rail cask systems (Ammerman and Sprung 2001) to support the performance of a proposed extra regulatory impact test of a full-scale rail cask. The 2001 quote for the HI-STAR cask system was updated in 2003 (Blessing 2003). Table O1-2 summarizes these cask system cost quotes. All quotes have been escalated to 2007 dollars.[c] The unit costs ($/kg U) shown in the table were calculated using the number of assemblies and total kg of uranium per cask presented in Table O1-1. As Table O1-2 shows, when expressed in 2007 dollars, cask system unit cost estimates range from $368/kgU to $547/kgU (for PWR SNF), and cluster around the escalated November 2003 $456/kgU unit cost quote for the HI-STAR cask system. More detailed cask system descriptions and cost component data are needed if differences in cask system unit costs are to be explained.

A phone conversation with a representative of Holtec International, the firm that manufactures and markets the HI-STAR spent fuel transportation cask system, provided more detailed cost data for this cask system. These data are summarized in Table O1-3, which presents low, modal, and high cost estimates for each costed item.

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[c] Cask and container costs have been escalated using the Bureau of Labor Statistics (BLS) Producer Price Index for Construction Machinery and transportation costs have been escalated using the BLS Producer Price Index for Line Haul Railroads. These (and many other) data can be obtained at www.bls.gov.

The range of each of these cost estimates reflects the difference between the 2001 and 2003 cost quotes and the fact that the difference between high end cost estimates and modal cost estimates are often larger than the difference between modal cost estimates and low end cost estimates (Morrow 2004). Table O1-3 shows that the modal value for the total cask system cost is \$5.36M. Interestingly, in Appendix E of Feizollahi et al.'s report, gives a cost of approximately \$3.75M for an earlier type of SNF shipping cask as of 1993. Conversion of this 1993 cost to 2007 dollars using the Urban Consumer Price Index (CPI) also yields an estimate of \$5.36M for the 2007 cost of a spent fuel cask system.

The data in Table O1-3 were used to perform a "1st of a kind/nth of a kind" cost analysis for the HI-STAR cask system. The data were also used to develop cost distributions for the single-use HI-STAR cask canister and for the reusable cask overpack and its two impact limiters by random (Monte Carlo) sampling of the cost distributions for the single-use canister and for the reusable cask system components. A present value analysis was then performed to convert the costs of the reusable items to a daily rental cost. This rental cost is combined with trip lengths (km) and shipment costs per km to estimate total shipment costs for SNF, MOX, and vitrified HLW. Figure O1-3 shows schematically the process through which the raw informal cost quotes were transformed into the information needed to estimate transportation costs for SNF, MOX, and vitrified HLW.

Table O1-2. Summary of Sandia informal quotes (direct costs).

	Direct Cost (Millions of 2007 dollars)				
Cask System	Multipurpose Canister	Transportation Overpack	Impact Limiter (two per overpack)	Complete Cask System	Unit Cost (\$/kg U)
HI-STAR: 2001 quote 2003 quote	0.66 0.55	2.08 2.63	1.42 0.82	5.58 4.82	528/547 456/473
BFS-TS125				5.84	553 (PWR)
NAC-UMS	0.81	2.92	0.30	4.33	410/451
NAC-STC	0.70	2.92	0.29	4.20	368/417

Table O1-3. HI-STAR cost components.

	Cost (Millions of 2007 \$)			
Component	Low	Modal	High	Comments
Licensing	8.75	10.94	21.88	High cost reflects additional expenses to obtain a license to transport high burnup SNF. Licensing costs are incorporated into cask system costs by the cask system manufacturer.
Initial fixtures for fabrication	4.38	5.47	10.94	This one time cost is incorporated into cask system costs by the cask system manufacturer.
Single-use multipurpose canister with SNF basket	0.44	0.55	0.77	2001 quote escalated to 2007 dollars is 0.66, which suggests a low end cost uncertainty of \$0.1M.
Cask overpack	1.97	2.63	3.50	2001 quote escalated to 2007 dollars is 2.08. Current quote of 2.63 (a 30% increase) is consistent with Holtec's suggestion of a pricing uncertainty of about 33%
Two impact limiters	1.31	1.64	1.97	Reusable
Ancillary equipment for welding & cask loading steps	0.55	0.66	0.88	This is a one-time cost.
Reusable cask components	3.72	4.92	6.35	Sum of Overpack, Impact Limiter, and Ancillary Equipment Costs
Total cask cost	4.27	5.36	7.11	Sum of canister, overpack, impact limiter, and ancillary equipment costs

Annual maintenance costs	Nominal			Because of the design of the single-use multipurpose canister, seals are not an issue. Thus, cask system maintenance will consist of occasional painting and other cosmetic activities
Expected lifetime (years) of the HI-STAR cask overpack and impact limiters	5	25	30	Design life is on the order of 100 years. A license extension every 5 years is initially easy to obtain, but becomes harder to obtain as material and fabrication specifications mature & become obsolete.

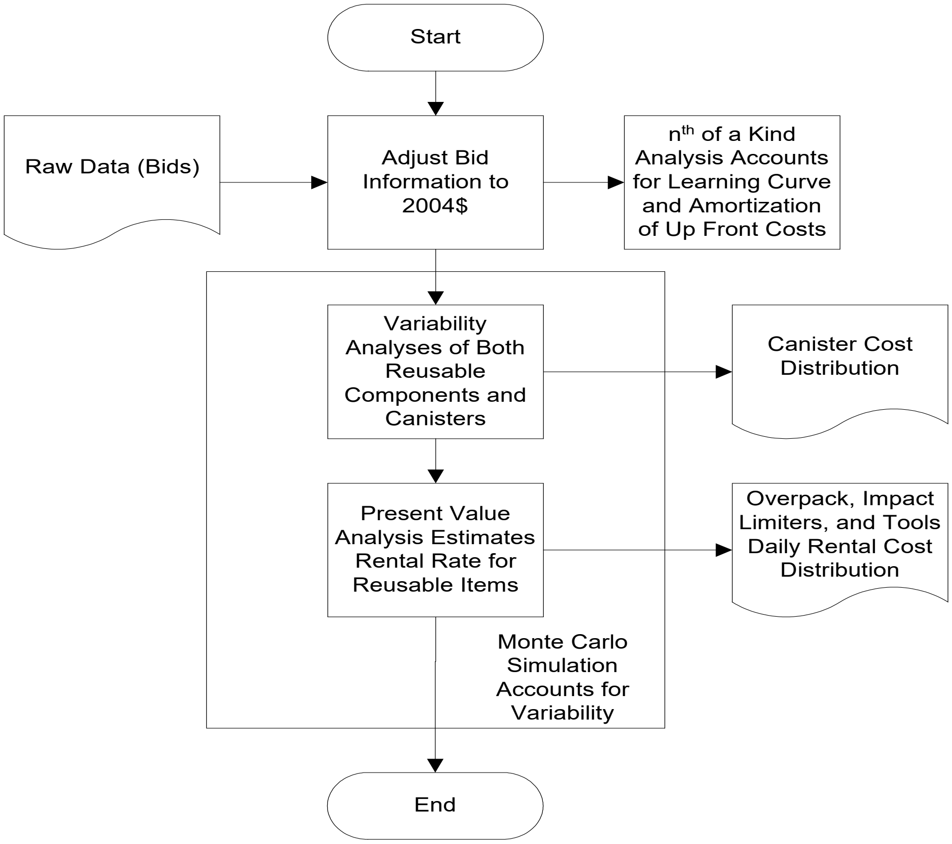

Figure O1-3. Process used to produce consistent cost estimates.

Bids were quoted as n^{th} of a kind (NOAK) costs by Holtec and thus should need no adjustment for the effects of the learning curve on or amortization of up-front costs. Holtec has sold a large number of HI-STORM storage cask systems and is no longer operating as a startup company. Although only a small number of HI-STAR storage/transportation cask systems have been sold to date, Holtec should be able to sell them for an n^{th} of a kind price. Nonetheless, for completeness, a typical "1^{st} of a kind/n^{th} of a kind" cost analysis was performed using the method of analysis presented in the Generation IV economic working group report (G4-EMWG 2003) and the modal HI-STAR cask system costs presented in Table O1-3. For this analysis, the n^{th} of a kind cost was assumed to be reached when the 200^{th} cask system was sold. Figure O1-4 presents the results of this analysis for the reusable cask system components (transportation overpack, impact limiters, and ancillary equipment). Inspection of the figure shows that if Holtec only sells a few HI-STAR cask systems, reusable cask system component costs might be about twice as high as the \$4.8M (escalated) n^{th} of a kind cost quoted by Holtec for reusable cask system components.

Canister Costs. Figure O1-5 presents the cumulative distribution of SNF and MOX canister costs that were developed by Monte Carlo sampling of the triangular distribution of canister costs specified in Table O1-3 for the HI-STAR cask system canister assuming that the procurement costs are about 10% of the canister purchase price (with the 10% procurement costs included, the low, modal, and high values for the triangular cost distribution for the canister become \$0.481M, \$0.602M, and \$0.842M). Figure O1-5 shows that canister costs (canister purchase price + canister procurement costs) might have a median value of about \$675,300 and could range from \$583,700 to \$796,700. Because vitrified HLW is stored at the vitrification plant before being shipped, HLW canister costs are treated as an operational expense in Module G1 and are not costed in this module.

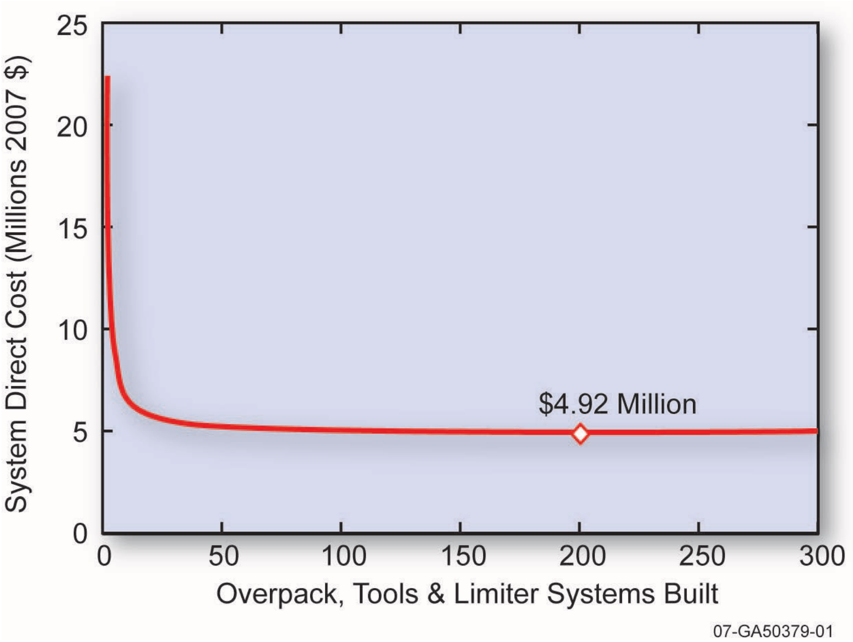

Figure O1-4. Nth of a kind curve for reusable items based on modal costs.

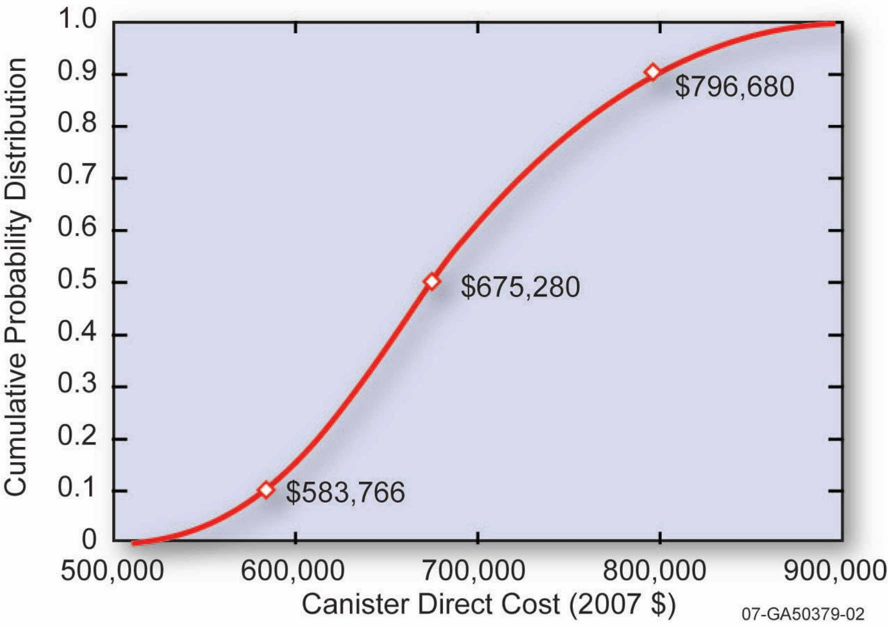

Figure O1-5. Cumulative distribution of multipurpose canister costs resulting from a triangular distribution of canister plus procurement costs.

Rental Costs of Reusable Cask Components. The present value analysis that was performed to develop daily rental costs for reusable cask system components (the cask overpack and its two impact limiters plus the cost of ancillary equipment) used the discounted cash flow methods recommended by Higgins (2001). Price was assumed to match cost at a discount rate of 10%. Table O1-4 presents the parameters that were used in this analysis. The utilization factor represents the fraction of days per year the HI-STAR cask system is assumed to be in use (earning money). Instead of applying an overhead percent to the cask system purchase price, a nominal Operations and Maintenance (O&M) cost ($117,100) was included in the analysis as a fixed cost. The analysis uses straight line depreciation based on the expected life of the cask system. For discounting purposes, year zero was assumed to be 2007. The first five parameters in this table were assumed to be fixed. The final two parameters, the price and useful life of the reusable items, were assumed to vary stochastically. Values for these two parameters were selected by random sampling from the distributions specified for these parameters in Table O1-3.

Table O1-4. Present value analysis parameters.

Fixed Parameters	Values			Units
Utilization Factor		0.9		Fraction
Inflation		3%		
Tax Rate		36%		
Discount Rate		10%		
O&M		$117,100		2007 $/year
Sampled Parameters	Low	Modal	High	
Price of Reusable Items	$3.72	$4.92	$6.35	Millions 2007 $
Useful Life	5	25	30	Years

The present value analysis was run 10,000 times. For each simulation, the calculated cost of the reusable cask components was adjusted to return a zero net present value based on the sum of discounted cash flows for all years of the analysis. Figure O1-6 displays the results of the analysis as a series of rental costs sorted low to high.

Inspection of Figure O1-6 shows that rental costs increase very rapidly once cumulative fractions pass 0.9. Thus, the 90th percentile rental cost is $3,057 per day while the 100th percentile rental cost is over $5,000 per day.

The very rapid increase of daily rental costs at high percentile values is caused by the very asymmetric shape of the triangular distribution assumed for the useful life of the reusable cask system components. This sharp dependence of daily rental cost on useful life is illustrated in Figure O1-7. Figure O1-7 presents a plot of 100 paired values of daily rental cost and the specific value of useful life that generated this daily rental cost. Specifically, the 100 plotted points are the first 100 outputs of the 10,000 calculations that underlie the results presented in Figure O1-6. Because the 10,000 calculations selected their variable input by random Monte Carlo sampling, these 100 results constitute a representative sample of the output of the full set of 10,000 calculations. Also plotted in Figure O1-7 is the best fit regression line through these 100 points. Inspection of Figure O1-7 shows that rental costs for reusable cask components are expected to be about $2,000 per day if the useful life of these components is about 25 years, while daily rental costs increase rapidly as useful life decreases passing $4,000 per day as useful life falls toward 5 years.

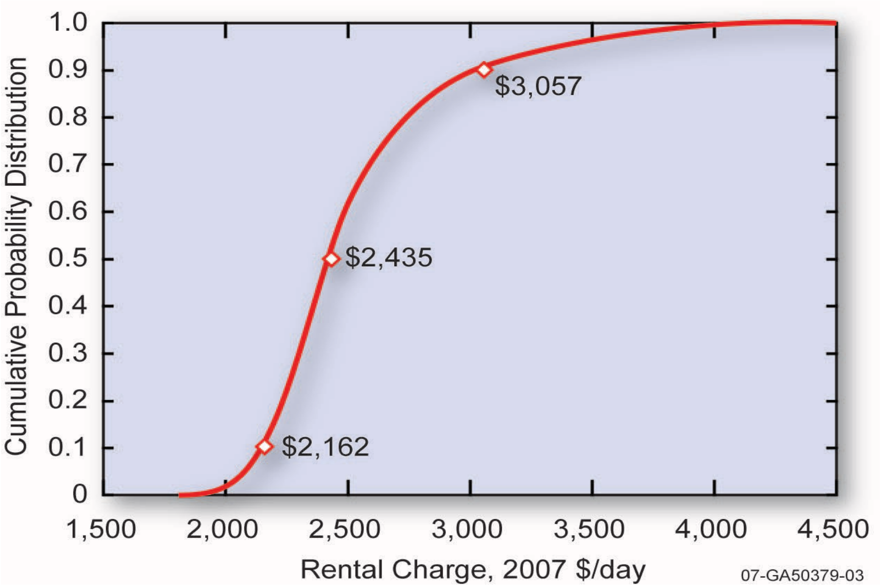

Figure O1-6. Distribution of daily rental cost for reusable cask components. Based on cash flow discounted at 10%.

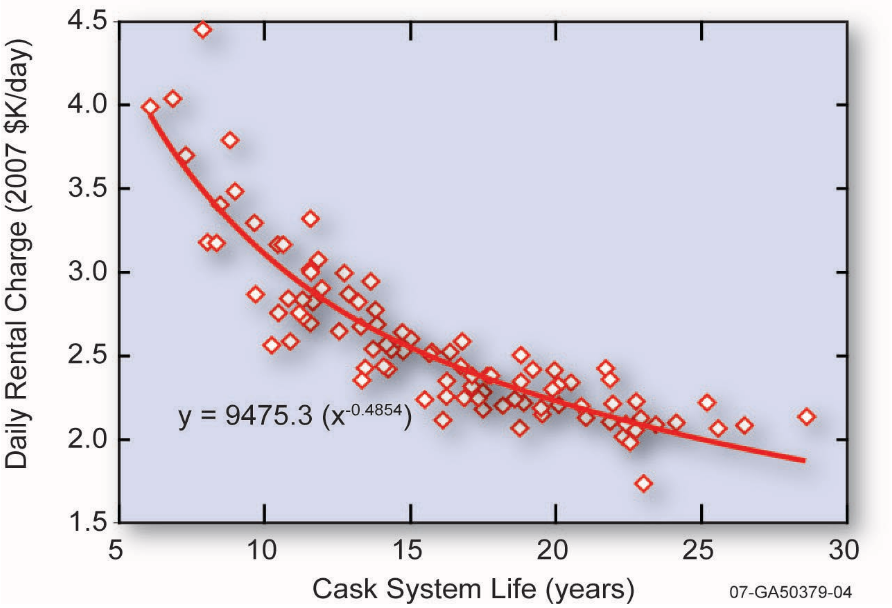

Figure O1-7. Variation of the daily rental rate for cask system reusable components with component useful life.

O1-6.2 RESULTS

Ten thousand sets of values for the 21 input parameters in the Cost Algorithm, for which distributions were developed, were selected by Monte Carlo sampling. Combination of each set of these values with the values specified for the 11 parameters that had single values generated 10,000 full sets of input for the Cost Algorithm. Running of the Cost Algorithm using these 10,000 sets of input allowed distributions of the five output parameters (fTotalCost, fPackCost, fLCost, fShipCost, fUCost) to be constructed. Output was developed for single shipments in the HI-STAR rail cask of:

- SNF from reactor sites to Yucca Mountain using the reactor sites to Yucca Mountain distribution of trip distances
- SNF from reactor sites to regional reprocessing facilities or interim storage sites using the reactor sites to regional sites distribution of trip distances
- MOX from regional fuel fabrication facilities to reactor sites using the reactor sites to regional sites distribution of trip distances
- Vitrified HLW from regional vitrification plants to regional interim storage sites using the regional sites to regional sites distribution of trip distances.

Monte Carlo sampling of parameters described by normal distributions or any other simple continuous algebraic formula is straightforward. The value of the independent variable in the algebraic formula is selected by Monte Carlo sampling, and then the value of the formula is used to calculate the value of the dependent variable. Selecting values for parameters represented by triangular distributions was done as follows. For any probability, P, the stochastic parameter X is calculated as

$$X = \begin{cases} P \le P_{mode} & X = min + \sqrt{P \cdot (max - min) * (mode - min)} \\ P > P_{mode} & X = min + \sqrt{(1 - P) \cdot (max - min) * (max - mode)} \end{cases} \tag{1}$$

where “X” stands for any of the parameters in Table O1-4 or for any other parameter represented by a triangular distribution,

$$P_{mode} = \frac{mode - min}{max - min} \tag{2}$$

and *max*, *min*, and *mode* are the high, low, and modal values used to specify the triangular distribution (Newendorp 1975).

Table O1-5 presents the input and output for one of the 10,000 calculations that were performed to develop the distribution of trip costs for the shipment of SNF from an operating reactor to Yucca Mountain. Table O1-5 shows that this single calculation predicts a total shipment cost of $831,000, a packaging cost of $733,000 ($725,000 for the single use canister and approximately $6,000 for the rental costs for the reusable cask system components), en route shipping costs of $850, and loading and unloading costs of $8,000 and $10,000, respectively (loading and unloading costs are not the same because different random numbers are used to select loading and unloading parameter values for parameters represented by distributions).

Table O1-5. Input and output for one of the ten thousand trip cost calculations for the shipment of SNF from operating reactor sites to Yucca Mountain (2005 $).

Inputs	Variable Name	Value	Units
SNF Shipped	iTons	20	Tonne U/yr
Weight of Canister Contents		43.27	Tonne Mat'l/yr
Canisters per Year		2	Cans/yr
Shipments per Year		2	Shipments/yr
Number of Packages per Vehicle	iNPackVeh	1	Can/Vehicle
Number of Vehicles per Train	iNPackVeh	1	Veh/Shipment
Number of Buffer Vehicles	iNBufVeh	2	Veh/Vehicle
Weight of Impact Limiters	iWWL	16.56	Tonne
Weight of Overpack	iWtOP	59.87	Tonne
Weight of Canister	iWtCan	18.02	Tonne
Weight of Canister Contents	iWtCanCont	21.64	Tonne
Cost per Shipment	fTotalCost	$830,715	$/Shipment
Cost per Year	fTot/year	$1,661,430	$/year
Annual Cost per Tonne of Heavy Metal	fTotMTiHM	$83.07	$/MTIHM/year
Annual Cost per MTIHM-Km	fTotMTiHM_km	$0.0753	$/MTIHM-km/yr
Cost of Packages	fPackCost	$733,250	$/Shipment
Number of Packages per Shipment	cNPack/Ship	1	Packages/Shipment
Cost of Multiuse Container	sCanCost	$724,955	$/Can
Overpack Rental Daily Cost	sOpCost	$2,155	$/year
Impact Limiter Rental Daily Cost	sILCost		$/year
Cost of Loading	fLCost	$7,844	$/Shipment
Overhead Factor	sLhead	2.02	
Loading Duration per Package	sLdur/Pack	14.02	Hr/Pkg/Person
Loading Duration per Shipment	cLdur/Ship	14.92	Hr/Shipment
Loading Wage Random Number	sLRand	0.1329973992	
Loading Supervisor Hourly Wage	sLS	$23.68	$/hr
Loading Rad Tech Hourly Wage	sLR	$10.68	$/hr
Loading Labor Hourly Wage	sLC	$10.68	$/hr
Number of Loading Oversight	iNLS	1	Person
Number of Loading Rad Technicians	iNLR	4	Persons
Number of Loading Crew Members	iNLC	11	Persons
Cost of En-Route Shipment	fShipCost	$79,953	$/Shipment
Distance Scenario		Reactor to Yucca Mountain	
Shipment Duration	cDays	1.92	Days/Shipment

Table O1-5. (continued).

Inputs	Variable Name	Value	Units
One-Way Trip Distance	strip	1104	Km
Average Speed	sSpeed	573	Km/Day
Convoy Vehicles	cNVeh	3	
Daily Rental Cost for Vehicles	sVehCost		$/day
Tonne Shipped	sTonnekm	139,156	Tonne-km
Shipper Tariff	sTarrif	$0.1064	$/Tonne-km
States Traversed	sStates	2	States
Individual State Fees	sSFee	$2,436	$/State
Dedicated Tran Cost	sDedVeh	$60,273	$/Trip
Cost of Unloading	fUCost	$9,668	$/Shipment
Overhead Factor	sUhead	2.885	
Unloading Duration per Package	sUdur/Pack	10.35	Hr/Pkg/Person
Unloading Duration per Shipment	cUdurShip	14.92	Hr/Shipment
Unloading Wage Random Number	sUS	$32.66	$/hr
Unloading Supervisor Hourly Wage	sUR	$14.68	$/hr
Unloading Rad Tech Hourly Wage	sUC	$14.68	$/hr
Number Pf Unloading Oversight	iNUS	1	Person
Number of Unloading Rad Technicians	iNUR	4	Persons
Number of Unloading Crew Members	iNUC	9	Persons

Figure O1-8 presents the distribution of total shipment costs developed by the Monte Carlo calculations. Because the calculation for SNF shipments from reactor sites to regional sites and for MOX shipments from regional sites to reactor sites yield the same cost distribution, Figure O1-8 only presents three distributions of total shipment costs. Inspection of this figure shows that the total costs in 2006 dollars for a single shipment of SNF or MOX are quite similar, averaging about $0.8M per shipment and ranging from about $0.6 to $1.1M per shipment in 2006 dollars. Total costs for a single shipment of vitrified HLW average about $0.2M and range from about $0.04M to $0.5M. Because the $0.6M cost of the SNF or MOX canister is included in the trip costs for the shipment, while the cost of vitrified HLW canisters is an operational cost for the vitrification facility, the cost distributions for SNF and MOX are shifted toward larger costs by about $0.6M. Thus, this figure indicates that total shipment costs are not strong functions of the differing trip distance distributions used in the three Monte Carlo trip cost calculations.

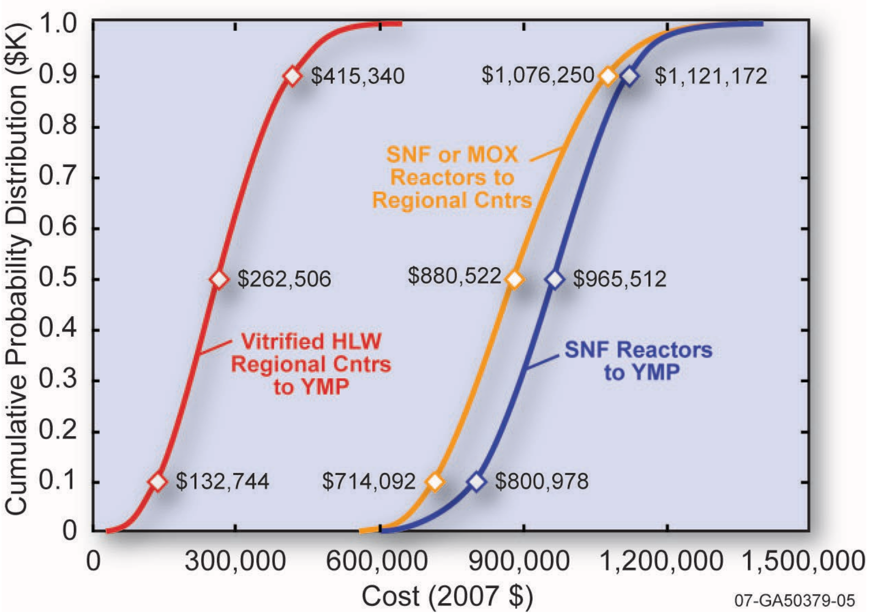

Figure O1-8. Distribution of total shipment costs for shipments of SNF, MOX, and vitrified HLW.

For each of the three Monte Carlo shipment cost calculations for which cost distributions are presented in Figure O1-7, average values for the total shipment costs and for the cask system cost the loading and unloading costs, and the enroute shipping costs that sum to give this total cost are presented in Table O1-6. Also presented in Table O1-6 are the fractional contribution of each cost component to the total cost and the average distance of each shipment and the weight of the material shipped.

Table O1-6 shows that SNF and MOX total trip costs depend mainly on packaging costs, secondarily on en-route shipping costs, and minimally on loading and unloading costs. For vitrified HLW, because canister costs are operational expenses for the vitrification plant, total trip costs depend mainly on en-route shipping costs.

Canister purchase costs, overpack, and impact limiter daily rental costs were developed above. Figures O1-5 and O1-6 present cumulative distributions for these two cost components. Figure O1-9 presents the cumulative distributions of packaging and en-route shipping costs that were calculated for the shipment of SNF or MOX between reactor sites and regional facilities.

Shipping Costs per Tonne per km. Division of the average value for the total trip cost by the product of the average trip distance and weight of the canister contents (the SNF, MOX, or vitrified HLW plus the weight of the canister basket and fuel assembly structures for SNF and MOX) yields the following values for the cost of shipping 1.0 tonne (1,000 kg) of each waste 1.0 km: $18.62 per tonne-km for shipping SNF from reactor sites to Yucca Mountain, $12.61 per tonne-km for shipping SNF or MOX from reactor sites to regional facilities, and $7.92 per tonne-km for shipping vitrified HLW from regional to regional sites.

Finally, an estimate of the annual shipping costs associated with the operation of one typical nuclear power plant for 1 year was developed as follows. First, the mass of the SNF generated by the operation of a typical nuclear power plant for 1 year is estimated. Next, the number of SNF shipments per year of reactor operation was estimated by dividing the mass of SNF generated by a typical reactor during 1 year of operation by the SNF mass carried in one spent fuel cask. Multiplication of the average number of SNF shipments per year of reactor operation times the sum of the average SNF shipment cost per trip and the average MOX shipment cost per trip then developed an estimate of the average annual shipping cost associated with the operation of one typical reactor for 1 year. These calculations are assumed for PWR fuel, whereas the cost for BWR fuel will be slightly higher since loading is slightly lower (Table O1-1)

Table O1-6. Average shipment cost (2007 dollars), trip distance (km), and weight (tonnes) of the contents of the canister for each of the three Monte Carlo shipment cost calculations.

	SNF Reactors to YMP		SNF or MOX Reactor to Regional Centers		Vitrified HLW Regional Centers To YMP	
	Value (2007 $)	Fraction	Value (2007 $)	Fraction	Value (2007 $)	Fraction
Total Cost	962,875	1.000	890,524	1.000	249,982	1.000
Packaging	669,726	0.695	664,645	0.746	18,811[a]	0.072
Shipping	275,276	0.286	208,029	0.234	211,143	0.860
Load & Unload	18,068	0.019	18,115	0.020	8,509	0.067
Trip Length, km	2351		3210		2,746	
Contents Wt, MT	22 10.6[b]	Ass'ys IHM	22 10.6[b]	Ass'ys IHM	12.4 29.8[c]	Glass IHM
Unit Cost	$18.62/MT-km $38.78/MTIHM-km		$12.61/MT-km $26.27/MTIHM-km		$7.92/MT-km $3.30/MTIHM-km	

a. Since the vitrified HLW canister cost does not enter this calculation, the packaging cost is the rental cost of the cask over-pack and its impact limiters

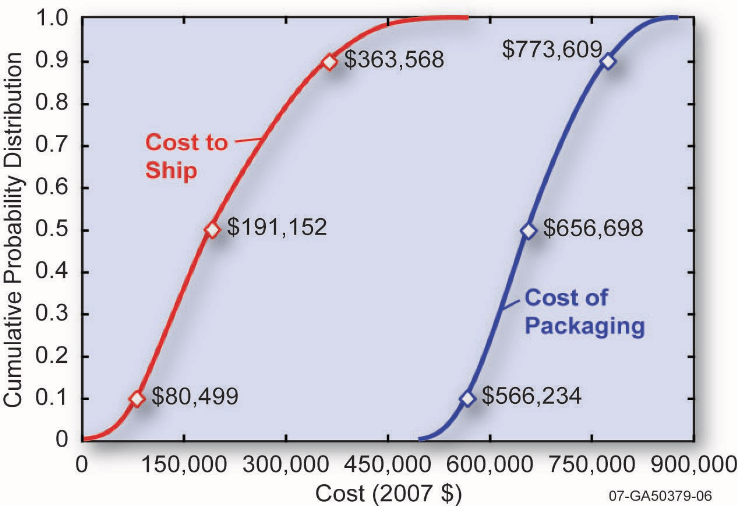

Figure O1-9. Cumulative distributions of packaging and en-route shipping costs for shipment of SNF or MOX between reactor sites and regional facilities.

Glass loading is assumed to be 0.12 MT fission products (FP)/MT glass. SNF contains approximately 0.001E MT FP/MTIHM if discharged at E GWd/MTIHM. Thus 1 MT glass is equivalent to 120/E MTIHM , or 2.4 MTIHM if E is assumed to be 50 GWd/MTIHM. The container holds 12.4 MT glass or 29.8 MTIHM equivalent.

Annual Shipping Costs per Operating Reactor. The amount of vitrified HLW and MOX generated per year by a single operating reactor will depend on the degree to which SNF is reprocessed, which is a scenario-dependent quantity. Consequently, annual shipping costs per operating reactor for vitrified HLW and MOX can not be meaningfully developed in this module. Of course, if all the fresh fuel used in an operating reactor is MOX, then the amount of MOX used per year by that reactor will be the same as the amount of SNF generated by that reactor.

The amount of SNF generated per year by a nuclear power reactor (iTons) depends on the plant's design power rating (GWe), its utilization factor or capacity factor, thermal efficiency, and burnup. Specifically,

MT SNF Produced = {Plant Rating • 365 • Capacity Factor]/[Thermal Efficiency • Burnup]. (3)

Figure O1-10 plots burnup data (GWd/ton) for the last 30 years. Figure O1-10 shows that the data are well fit ($R^2 = 0.9658$) by a straight line with a slope of 0.928. Thus, burnup has historically been increasing linearly with time. Discussions with nuclear power scientists indicate that the projected future increases in burnup, predicted in the figure by extrapolation of the historic data, are both feasible and economically attractive. Because they are economically attractive, it is likely that a technical basis will be developed for increasing the current regulatory burnup limit. Hence, a reasonable range for burnup would be from the current 35 GWd/ton to something like 75 GWd/ton several decades hence.

Reasonable values of these parameters for modern nuclear power reactors are: Plant Rating = 1 GWe; Capacity Factor = 0.9, and Thermal Efficiency = 33%. Use of these parameter values, the preceding expression for SNF produced, and the linear dependence of burnup on time presented in Figure O1-10 now allows the variation with burnup of the annual fuel consumption (MTIHM) of a typical 1 GWe nuclear power reactor to be calculated. Division of the consumption results by 10 tonnes, the fuel capacity in MTIHM of the HI-STAR cask, then allows the number of SNF shipments per year for a typical nuclear power plant to be estimated.

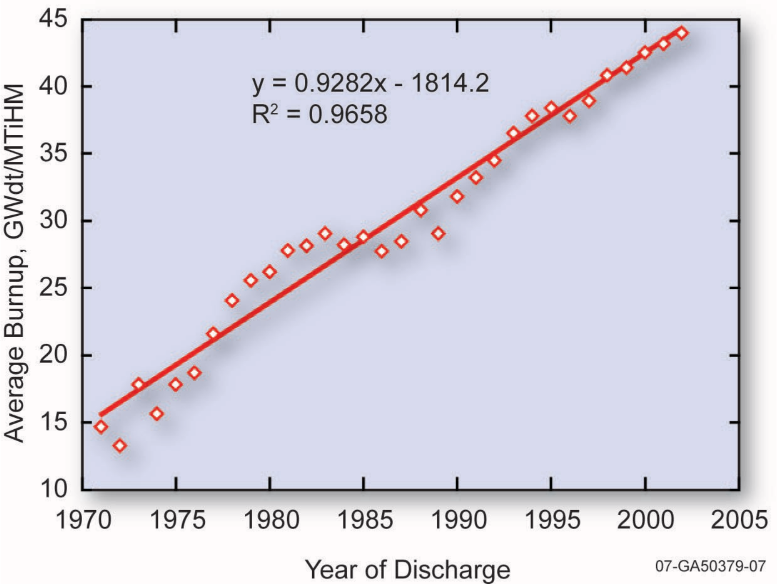

Figure O1-10. Extrapolation of fuel burnup data.

Figure O1-11 presents the results of these calculations. Inspection of Figure O1-11 shows that for a typical 1 GWe nuclear power plant annual fuel consumption and the number of spent fuel shipments per year are respectively about 25 MTIHM and 2.5 shipments/year, if fuel burnup is 40 GWd/ton and about 15 MTIHM and 1.5 shipments/year, if fuel burnup is 70 GWd/ton. Thus, two SNF shipments per year per operating reactor is a reasonable factor to use to convert trip costs into annual SNF shipping costs. Application of this factor to the average trip cost of $0.88M for shipping SNF or MOX yields an annual SNF shipping cost per reactor of about $1.76M. Of course, if a reactor is fueled using only MOX, because the cost per trip for MOX is the same as that for SNF, annual MOX + SNF shipping costs for this reactor will be double, or $3.25M.

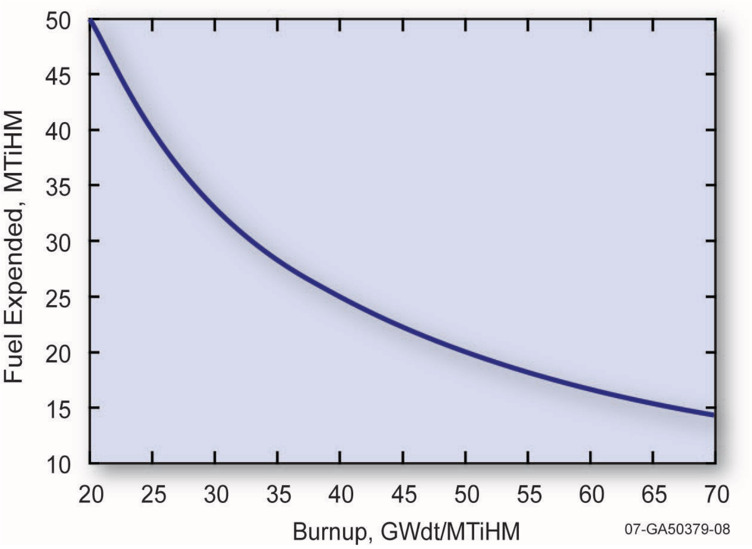

Figure O1-11. Projected SNF production from a typical nuclear power plant.

O1-7. DATA LIMITATIONS

Because spent fuel pools at commercial reactors are rapidly filling up, substantial quantities of SNF will need to be shipped in transportation casks to interim or permanent storage facilities in the near future. However, at present, there is very little data available on the estimated or actual costs of shipping SNF, MOX, or vitrified HLW. Cost estimates or data for these shipments are sparse because neither a permanent repository for high-level commercial radioactive wastes nor regional monitored retrievable storage facilities for such wastes currently exit. Consequently, shipments of SNF, MOX, or vitrified HLW are rare. A U.S. Department of Energy Report (2001) contains some estimates for the costs of shipping SNF, but they are specific to the current inventory of SNF and to specific shipping campaigns to the proposed Yucca Mountain repository.

Because the cask systems and railroad rolling stock, that would be used to ship SNF, MOX, and vitrified HLW by rail, are already commercially available technologies, the shipping cost estimates developed in this module, though approximate, are not likely to be highly uncertain. Thus, upper bound (downside) estimates of shipping costs should not be substantially larger than the central estimates developed in this module. However, lower bound (upside) estimates could be substantially smaller than the central estimates developed here if the nuclear fuel cycle becomes much larger in the future, whereupon substantial economies of scale might be achievable.

The HI-STAR transportation cask system that is the basis of the cost estimates developed in this module uses a single-use multipurpose canister that has a welded lid, plus a reusable cask overpack and reusable impact limiters to support shipment of SNF. If the HI-STAR multipurpose canister can be used for permanent storage, the cost of transferring SNF from the multipurpose canister to a permanent storage canister will be eliminated and extensive periodic maintenance on the cask system will not be required. Other cask systems that do not use a canister or use a reusable canister will have lower up-front costs but higher maintenance costs. Limited investigation suggests that life-cycle costs for alternative cask systems are similar to those calculated in this module for the HI-STAR cask system. If future model development permits the use of cask system cost data for any cask system, then the suggestion that transportation costs will not vary greatly with cask system should be examined in more detail.

The cost estimates developed in this module contain no costs for any capital facilities needed for the packaging of SNF, MOX, or vitrified HLW. It is assumed that either these costs are incorporated into the capital cost of the power plant, the recycled fuel fabrication plant, or the vitrification facility, or the choice of cask system obviates the need for expensive transfer equipment. Finally, significant cost savings may be obtained if the cask systems used and the equipment at the facilities to which these HLWs are shipped are designed to be mutually compatible. Once a full nuclear fuel cycle economic model has been developed, cask system/storage system costs should be reviewed to identify any significant cost savings that would result from the use of mutually compatible equipment designs.

O1-8. COST SUMMARIES

The module cost information is summarized in the What-It-Takes (WIT) cost summary in Table O1-7. The summary shows the reference cost basis (constant year $U.S.), the reference basis cost contingency (if known), the cost analyst's judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, and selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. Refer to Section 2.6 in the main section of this report for additional details on the cost estimation approach used to construct the WIT table.

Table O1-7. What It Takes (WIT) Cost summary table (2007 $) – based on YMP Data.

Reference Cost	Low Cost (Upsides)	High Cost (Downsides)	Selected Value (Nominal Cost)
Canister Purchase	566,000	773,000	657,000
Cask System Rental			
$/day	2,100	3,060	2,430
$/trip	7,600	32,400	17,900
Total Costs			
SNF, Reactors to YMP	804,000	1,122,000	966,000
SNF/MOX Between Reactor & Reg'l Cntr	714,000	1,077,000	881,000
HLW to YMP	133,000	417,000	263,000
Cost/kg IHM			
SNF, Reactors to YMP	75.90	106.30	91.59
SNF/MOX Between Reactor & Reg'l Cntr	67.60	102.00	83.40
HLW to YMP	4.50	14.00	8.80
Cost/ MTIHM-km			
SNF, Reactors to YMP	32.30	45.20	38.90
SNF/MOX Between Reactor & Reg'l Cntr	21.10	31.30	26.00
HLW to YMP	1.60	5.10	3.20

Table O1-8. Code-of-accounts data (median costs per operating reactor, millions 2006 dollars).

AFCI Code of Accounts Number	Code of Accounts Description	Cost Per Operating Reactor ($ Million)	Comments
7	Annualized O&M cost Once-Through Reprocess Recycle	 1.93 1.95 3.71	Once-Through considers only SNF to YMP. Reprocess considers SNF to Regional Center and HLW from there to YMP. Recycle considers MOX from Regional Center to Reactor, SNF return and HLW to YMP.
9	Annualized financial costs		
	Total Annual Operating Costs Once-Through Reprocess Recycle	 1.93 1.95 3.71	

The What It Takes table above lists costs by several parameters. These costs may be is somewhat obsolete as they were based on Yucca Mountain cost estimates. Similarly, cost per kgiHM per kilometer is a useful metric only when the distance to be shipped is known.

The information above estimates have been revisited and re-evaluated by the DOE's Used Fuel Disposition (UFD) Campaign System Architecture Evaluation (Nutt, 2012). This evaluation is similar to the original methodology in that used nuclear fuel (UNF) is taken from a reactor and sent to a repository, or to a regional storage facility before transportation (potentially years later) to a repository. However, it does not tie directly to Yucca Mountain. Moreover, the original analysis assumed the existence of six regional centers; the current evaluation uses only one.

Additionally, the original methodology assumed 20 MTHM shipped per year; the new methodology assumes between 1500 and 6000 MTHM per year. This is a significant difference that directly impacts the transportation costs by spreading the capital and operations costs over a much greater mass flow. The result is that the new methodology shows a much lower cost of transportation for UNF from the reactor site to the repository. Interestingly, the cost of transportation from the reactor site to the repository via the regional facility does not differ appreciably from the previous revision.

Table O1-9 What-It-Takes (WIT) Cost Summary Table – Based on Systems Architecture Study

Transportation Option	Cost per kilogram of material for transportation			
	Low Cost	Mode Cost	Mean Cost	High Cost
From Reactor to Repository (2012$)	$21.9/kg	$24.5/kg	$24.5/kg	$27.1/kg
Escalated to 2020$	**$24.8/kg**	**$27.8/kg**	**$27.8/kg**	**$30.7 /kg**
From Reactor to Central Storage Facility to Repository	$95.0/kg	$97.5/kg	$98.0/kg	$100.0/kg
Escalated to 2020$	**$107.7/kg**	**$110.5 /kg**	**$110.5/kg**	**$113.4/kg**

For this update, the UFD evaluation high- and low-end reported values corresponding to a 2055 repository start date are used to define the high cost and low cost values. The mean between the high and low is used as the nominal cost. Figure O1-12 shows the probability distributions for the above unit transportation costs.

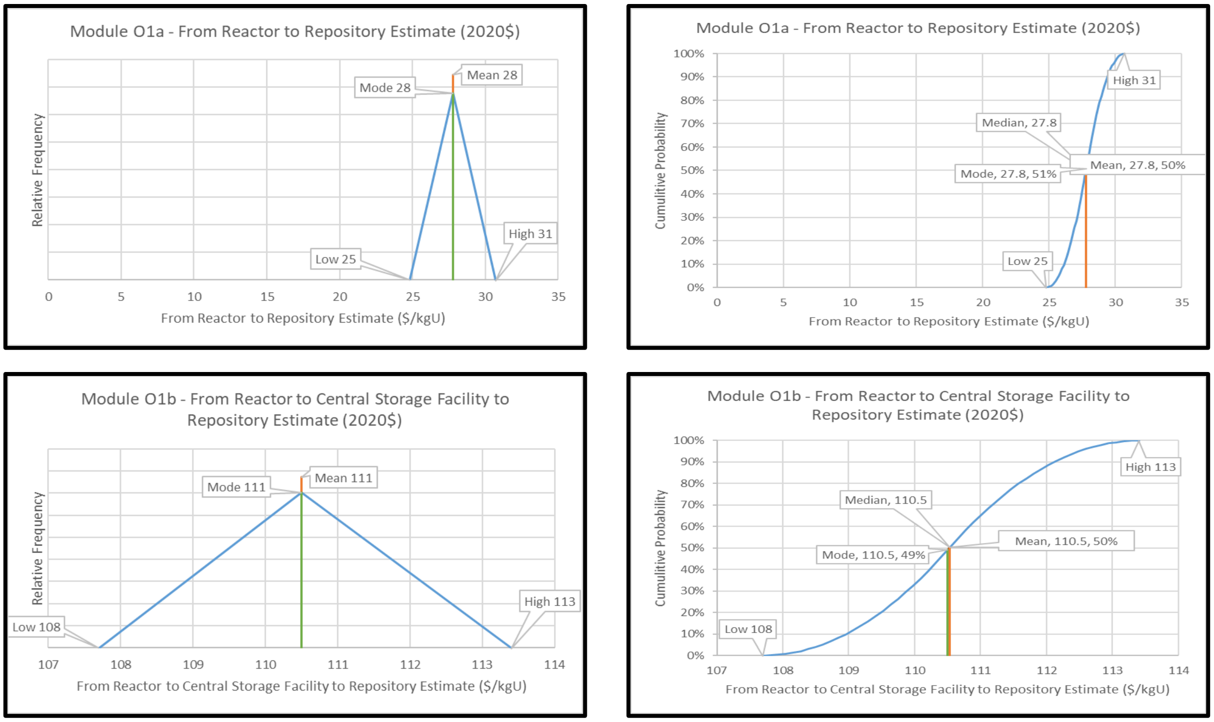

Figure O1-12 Probability Distributions for SNF Unit Transportation Costs

O1-9. SENSITIVITY AND UNCERTAINTY ANALYSES

During the development of shipment cost estimates, a number of sensitivity calculations were performed. These sensitivity calculations are summarized and discussed in this section. Figure O1-5 shows that the 10th, 50th, and 90th percentile values for the cost of single-use canisters are respectively about \$0.566M, \$0.657M, and \$0.773M. Thus, the cost of an actual canister will probably differ from the best estimate cost by at most about 20%. Figure O1-6 shows that the 10th, 50th, and 90th percentile values for the daily rental cost of the reusable cask components (the overpack and its impact limiters) are respectively about \$2,160; \$2,430; and \$3,060. Thus, the actual daily rental cost for the reusable cask components will probably differ from the best estimate cost by at most about 30%.

Figure O1-4 presents the results of a "1st of a kind/nth of a kind" analysis of the costs of reusable cask system components. This figure indicates that the purchase cost of the reusable cask components is expected to be about \$4.9M so long as the manufacturer of the cask system sells at least 40 cask systems. The figure also shows that the cost of the reusable cask system components will rapidly increase as the number of cask systems sold falls below 40 systems and could approach \$10M if less than 10 systems are sold. Figure O1-7 shows that the daily rental cost for the reusable cask system components depends strongly on the useful life of these components. For example, if these components are used for 25 years, then the rental cost is about \$2,170 per day. However, if component life is only 5 years, then the rental cost can exceed \$4,700 per day. Thus, rapid technological obsolescence could significantly increase the daily rental costs for reusable cask system components. For example, current SNF cask systems are designed to transport 5-year cooled SNF. Therefore, without additional cooldown time, the thermal capacities of current cask systems will not allow them to be completely filled when they are transporting high burnup SNF. Thus, if the nuclear fuel cycle shifts largely to high burnup fuels and if longer cooldown time is uneconomic, then either these casks will have to be replaced, or when shipping high burnup SNF, they will not be able to be fully loaded. Either of these outcomes could increase shipping costs significantly.

Annex OX to this module shows that shipment distances range form 0 to 5,000 km and average about 2,500 km. It also shows that regular freight trains travel about 800 km per day. Because dedicated trains will make fewer stops than regular freight trains, they might cover 1,900 km = (80 km/hr) (24 hr in a day). The Annex further shows that for a 2,500 km trip, the cost per ton-km is about $0.12. Therefore, because a fully loaded SNF cask weighs about 125 tonnes, the weight-based shipping cost of this cask will be about $37,500 = ($0.12 tonne-km)(125 tonnes)(2,500 km). The cost of renting the cask's reusable components will be no more than $6,560 = ($2,100/day)(2,500 km)/(800 km/day) for this trip. Because both of these costs are small compared to the $650,000 cost of an SNF canister, shipments of SNF and MOX will be relatively insensitive to shipment distance or to weight-related shipping costs.

States may try to levy a tariff on each shipment of a highly radioactive material that enters their state. However, even if state tariffs for shipments of highly radioactive materials survive court challenges, because these tariffs are not expected to be much larger than about $2,500 per state traversed, and because the average shipment of SNF, MOX, or vitrified HLW will traverse perhaps eight states, state tariffs should not exceed $20,000. Therefore, the state tariffs will constitute a minor component of total shipping costs. Finally, because shipping costs depend minimally on loading and unloading costs, none of the uncertainties associated with labor rates are important.

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Module O2

Transport of Nuclear Fuel and Low-Level Radioactive Materials

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O2 REVISION LOG

Rev.	Date	Affected Pages	Revision Description
	2004	O2-All	**Version of AFC-CBR in which Module first appeared:** 2004 as Module N, which also included transportation of SNF and HLW. In the 2006 AFC-CBR it was decided to include this Module in a two-part Module O as Module O2. SNF and HLW Transportation was renamed Module O1 Nuclear Fuel and Low Level Radioactive material transportation became Module O2
	2006	O2-All	**Version of module in which new technical data was used to establish “what-it-takes” unit cost ranges:** 2006 • 2006 data was escalated to 2017$ for this latest revision (35% increase in unit cost)
		O2-All	**New technical/cost data which has recently become available and will benefit next revision:** None.
	2021	All	Re-formatted module consistent with revised approach to release of the AFC-CBR and escalated cost estimates from year of technical basis to escalated year 2020. Cost estimates are in US dollars ($) of year 2020.

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Module O2
Transport of Nuclear Fuel and Low-Level[d] Radioactive Materials

This sub-module, O2, deals with the transport of nuclear fuel and low-level radioactive materials; this is essentially anything not covered by sub-module O1.

O2-MD. SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year 2020 for this FY21 update.**
- **Nature of this FY21 Module update from previous AFC-CBRs:** Escalation only
- **Estimating Methodology for latest technical update from which this FY21 update was escalated:** Transportation costs for 9 types of fuels or radioactive substances were developed in a bottom-up estimating manner by Sandia National Laboratory. This data included the costs of the special containers used for waste shipment. In 2009 some cost data, such as that for uranium hexafluoride, was revised to reflect the use of reusable containers.

O2-1. BASIC INFORMATION

This module develops cost estimates for the shipment of nuclear fuel and low-level radioactive materials between nuclear fuel cycle facilities. Table O2-1 presents a summary of the 14 facility pairs (an origin facility and a destination facility) between which low-level radioactive materials are shipped. Table O2-1 lists these 14 origin/destination facility pairs and the module that describes each facility. Table O2-1 also specifies for each facility pair the material that is shipped from the origin facility to the destination facility and one or more packages used to ship the material. Although Table O2-1 shows that enriched UF_6 (EUF_6) may be transported in at least three different packages and depleted UO_2 (DUO_2) in at least two different packages, the cost analyses presented in this module examined only one package for each material shipped. For example, the package examined for EUF_6 was the UX-30 package, and for DUO_2 it was the CHT-OP-TU package. Thus, trip costs were developed for nine packages.

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[d] "Low-Level" is a widely used term defined only within the U.S. Department of Energy (DOE). In effect, it means anything other than "high-level." The NRC categorizes "low-level" materials into those that are suitable for land disposal and those that are not. There are three classes of land disposal materials (A, B, & C), with the radioactive content increasing from A through C. The NRC also recognizes a type of "low-level" material that is greater than Class C (GTCC) and which is NOT eligible for land disposal. Some of the materials discussed here may be in the GTCC category.

Table O2-1. Fourteen pairs of an origin facility and a destination facility, the material shipped between these facilities, and typical shipment packages.

Flow Stream	Modules		Origin Facility to Destination Facility	Material Shipped	Typical Packages
	From	To			
1	A	B	Mill to UO_X Conversion	Yellow Cake, U_3O_8	55-gal drums
2	B	C	UO_X Conversion to Enrichment	UF_6	Paducah Tiger
3	C	D1	Enrichment to Fresh Fuel Fabrication	EUF_6	UX-30 NCI-21PF-1 ESP-30X
4	C	F2/D2	Enrichment to Recycled Fuel Fabrication		
5	C	K	Enrichment to DUF_6 Conversion	DUF_6	Paducah Tiger
6	K	F2/D2	DUF_6 Conversion to Recycled Fuel Fabrication	DUO_2 powder or pellets	CHT-OP-TU (B) ANF-250
7	K	J	DUF_6 Conversion to Surface Disposal	DUO_2	
8	F	B	Reprocessing to UOX Conversion	UOX	
9	F	F2/D2	Reprocessing to Recycled Fuel Fabrication	TRU/TRUOX	9975 (B)
10	F	E3	Reprocessing to Decay Storage	TRU, FP[a]	RH-TRU 72B (B)
11	F	J	Reprocessing to Surface Disposal	LLW, UOX	CHT-OP-TU (B)
12	E3	F2/D2	Decay Storage to Recycled Fuel Fabrication	TRU	RH-TRU 72B (B)
13	E3	J	Decay Storage to LLW Surface Disposal	FP[a]	CNS10-160B (B)
14	D1	R	Fresh Fuel Fabrication to Reactor	Fresh PWR Fuel Assemblies Fresh BWR Fuel Assemblies	MCC-4 SP-1,2,3

a. FP, as used in the table above, means fission products such as cesium, iodine, strontium, & technetium.

Low-level radioactive materials can be shipped by truck or rail. Because they are usually shipped by truck, the shipping costs developed in this module assume shipment using 18-wheel tractor/semi-trailer trucks that are fully loaded (i.e., the truck is loaded with the largest number of packages that it is allowed to carry). Moreover, because the vulnerability risks posed by these materials are small, it is assumed that each shipment consists of one truck (i.e., no shipments are made by a convoy of trucks) and also that the truck is not guarded by any escort vehicles.

Many of the packages listed in Table O2-1 are low-specific activity or Type-A[e] packages. Those that are not are indicated by "(B)." Transportation costs for materials shipped in low-specific activity or Type-A packages consist of the cost of the packaging,[f] loading costs at the shipment origin, shipping costs while in transit, and unloading costs at the shipment destination. For Type B packages, it may be necessary to add costs for certification/recertification and for periodic testing and maintenance.

The objective here has been to establish a cost estimate, not to prejudge which packagings might eventually be selected for actual use. In some cases, the certificates currently issued for the packagings assumed may require some amendment to be used for the purposes indicted in Table O2-1. In particular, the 9975 has been certified by DOE under authority granted for weapons-related work and materials.

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[e] Transportation packages fall into two categories, depending primarily on radioactive content, with Type A having lower radioactive content than Type B. As long as the enrichment level is less than 5%, virtually all packages containing unirradiated uranium are Type A. However, fairly small amounts of TRU can cause a package to be classified as Type B; the threshold for Pu-239, for example, is only 0.087 g.

[f] In this section, the term "packaging" refers to the devices into which radioactive material is placed for shipment—in other words, the shipping container. The term "package" refers to the container and its contents.

Acceptance by the NRC may be required for “commercial” materials. Such acceptance is considered highly likely.

O2-2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

At the facility where it is generated, each of the materials listed in Table O2-1 is loaded into a package designed and certified to carry that material. After being loaded onto a truck, the packages are transported from their origin facility to their destination facility where they are unloaded from the truck. At all destination facilities except near surface disposal facilities, the shipped material is removed from the shipping package so that it can be converted to a new material.

O2-3. PICTURES AND DIAGRAMS

Figure O2-1 presents photographs of two typical Type-A packagings, a carbon steel 55-gallon open top drum used to ship yellow cake, and a UX-30 packaging used to ship enriched UF_6.

Figure O2-1. Typical Type-A packagings.

O2-4. MODULE INTERFACES

Columns two and three of Table O2-1 list fourteen pairs of modules that describe the origin facility and the destination facility for each material shipped. The table shows that low-level radioactive material fuel cycle shipments originate at the following seven types of facilities: uranium mills (Module A), UO_2 to UF_6 conversion facilities (Module B), UF_6 enrichment facilities (Modules C1 and C2), depleted UF_6 (DUF_6) conversion facilities (Modules K1, K2, and K3), SNF reprocessing facilities (Modules F1 and F2/D2), interim decay/storage facilities (Module E3), and fresh fuel fabrication facilities (Module D1). The table also shows that the low-level radioactive materials produced at these six types of facilities are shipped to one or more of the following seven types of facilities: UO_2 conversion facilities (Module B), UF_6 enrichment facilities (Modules C 1 and C2), fresh fuel fabrication facilities (Module D1), recycled fuel fabrication facilities (Module F2/D2), depleted UF_6 conversion facilities (Modules K1, K2, and K3), interim decay/storage facilities (Module E3), near surface low-level waste disposal facilities (Module J), and nuclear power plants (R Modules).

O2-5. SCALING CONSIDERATIONS

The analysis show that the cost of shipping low-level radioactive material in single use packagings depends principally on the purchase price cost of the packaging or of any expensive single use packaging components. Thus, for a single shipment of one package, shipping costs will be relatively invariant. However, if any of the packagings assumed to be single-use in this module are actually used multiple times, then, very approximately, shipment costs should vary inversely with the number of times that the packaging is reused. In addition, the annual shipping costs for a low-level radioactive material will not equal the product of its annual cost per operating reactor and the number of operating reactors. This is because some of the low-level radioactive materials shipped will be recycled, and thus the amount of fresh fuel needed per operating reactor will depend on the amount SNF that is being reprocessed.

O2-6. COST BASES, ASSUMPTIONS, AND DATA SOURCES

O2-6.1 INPUT PARAMETER VALUES

Annex OX to Module O derives the algorithms used to estimate transportation costs and provides values for the parameters that are not packaging-specific. Table O2-2 presents the packaging-specific input parameters. In Table O2-2:

- The values of package loaded weights and package contents weights were extracted from the package Certificates of Compliance
- Package costs were estimated (see Section O2-5.2 for details) from literature data and discussions with two shippers of low-level radioactive materials and a manufacturer of low-level radioactive material packages
- The number of packages carried per truck was based on the package carrying capacity of the floor space of an 18-wheel tractor/semi-trailer truck, reduced where necessary to reflect shielding and criticality limits
- The low, modal, and high values for the triangular distribution used to represent package loading and unloading durations were selected based on the experience of Sandia National Laboratories technical staff.

Although a specific package loading parameter and its analogous unloading parameter could have different triangular distributions (different low, modal, and high values), the calculations presented here assumed that they were the same. Accordingly, as is shown in Table O2-2, the triangular distribution for the overhead factor on wages for loading is the same as for unloading, and the distribution for time required to load a package is the same as to unload.

Table O2-2. Parameter values for packaging-specific parameters.

				Single Value Parameters				Load/Unload Distribution		
Material Carried	Name	Certificate	Packages per Truck	Cost (2007$)	Loaded Wt. (lb)	Contents (kg HM)	Trip Routes	Lo	Mode	Hi
Yellow Cake	55-gal drums	Industrial Package	104	$110	440	139	Mills to Regional	0.167	0.25	0.5
UF_6, DUF_6	Paducah Tiger	6553/AF	1	$211,580	40,000	6,450	Regional to Regional	6	12	24
EUF_6	UX-30	9196/AF-85	4	$24,540	8,270	1,540		1.5	2	3
DUO_2, UOX, LLW	CHT-OP-TU	9288/B(U)F-85	10	$27,890	3,757	643		0.5	1	1.5
TRU/TRUOX	9975	9975/B(M)F-85(DOE)	22	$8,030	404	2		0.167	0.5	0.75
FP	CNS10-160B	9204/B(U)-85	1	$725,000	72,000	2,630		18	24	36
TRU, FP	RH-TRU 72B	9212/B(M)F-85	1	$725,000	45,000	1,475		18	24	36
Fresh Fuel Assemblies	MCC-4	9239/AF	2	$49,080	10,500	2 PWR	Regional to Reactors	4	6	8
	SP-1,2,3	9248/AF	3	$29,000	2,800	2 BWR		4	6	8

As Table O2-2 indicates, the cost calculations performed in this module require a distribution of possible shipment distances. Except for shipments of yellow cake from uranium mills to conversion facilities and of fresh fuel assemblies from fresh fuel fabrication facilities to nuclear power reactors, all the other shipments considered will be between regional facilities. Accordingly, three distance distributions are needed, between uranium mills and conversion facilities located at regional sites (Mills to Regional), between regional conversion, enrichment, reprocessing, fuel fabrication, interim decay/storage, and near surface disposal facilities (Regional to Regional), and between regional fresh fuel fabrication facilities and nuclear power reactors (Regional to Reactors). These are developed in Annex OX.

Before being placed into service, Type-A packages must be certified by the Department of Transportation (DOT) (49 CFR 173.417 2006) and also by NRC (10 CFR 71 2005), if they will carry significant quantities of fissile materials. Because almost all the materials listed in Table O2-1 contain uranium or plutonium, all the packages listed in Table O2-1 should have been certified by both DOT and NRC. Type B packages are certified by the NRC.

Because some Type-A packages used to ship nuclear fuel cycle low-level radioactive materials are likely to be reused, when estimating shipping costs, packaging costs should be amortized over the useful life of the packaging and expressed as a rental cost. This was performed for all the Type B packagings, whereas Type A packagings were considered single use. In retrospect, this is probably appropriate only for the 55-gallon drum. Some cost savings could be achieved by considering the other Type A packagings to be multiple use containers and a rental charge devised to evaluate the cost. Finally, because the packagings examined in this module are all commercially available, the data presented in Table O2-2 are entirely adequate for the scoping cost analyses performed in this module.

O2-6.2 PACKAGING COSTS

The packaging costs developed for this module consider two types of packages. Some materials will be shipped in Type B packages. These packages are used for the more intensely radioactive materials; they are certified by the NRC; and they tend to be complex in design and relatively expensive per unit of payload. Less intensely radioactive materials are shipped in Type A packages, which are generally simpler in design; certified by the DOT, and/or the NRC (NRC certification is required if they carry fissile materials). In Table O2-3, the Type B Packages are indicated by a (B) following the name. The remaining packages are Type A packages. Although these radioactive materials can be shipped by either truck or rail, the costs developed in this module assume shipment by truck.

Table O2-3 again lists the nine packagings considered in this module, presents for each packaging the name of the packaging manufacturer, the approximate cost of the packaging, the number of packages that can be transported by an 18-wheel tractor/semi-trailer truck, and the material carried in the package. All packaging costs have been adjusted to 2007 dollars using the producer price index for hardware. More detailed packaging descriptions and cost component data would be needed if differences in packaging unit costs are to be explained.

Table O2-3. Approximate packaging costs and manufacturers.

Material Carried	Name	Packages per Truck	Cost per Package (2007 $)	Manufacturer
Yellow Cake	55-gal drum	104	$110	LabelMaster, Inc.
UF_6	Paducah Tiger	1	$211,580	US Enrichment Corp.
Enriched UF_6	UX-30	4	$24,540	Columbiana Hi Tech Front End LLC
LLW, DUO_2, UOX	CHT-OP-TU (B)	10	$27,890	Columbiana Hi Tech Front End LLC
TRU/TRUOX	9975 (B)	22	$8,030	DOE - Savannah River Operations Office
FP	CNS10-160B (B)	1	$725,000	Duratek
TRU, FP	RH-TRU 72B (B)	1	$725,000	DOE
Unirradiated PWR Fuel Assemblies	MCC-4	2	$49,080	Westinghouse Electric Company
Unirradiated BWR Fuel Assemblies	SP-1,2,3	3	$29,000	Framatone ANP

Costs to Acquire Packagings. Informal cost quotes for the UX-30, the CHT-OP-TU, and the 9975 packagings were obtained by phone calls to and email exchanges with a representative of the manufacturer of each of these packagings. The cost of the RH-TRU 72B packaging was taken from one of the weekly newsletters published by the Waste Isolation Pilot Plant (TRU TeamWorks 2003). The cost and capacity of the 55 gallon open-head steel drums used to ship yellow cake were obtained from the one manufacturer's 2005 catalog (LabelMaster, Inc. 2005).

When cost data could not be directly obtained for the remaining seven packagings, packaging cost estimates were developed as follows. For the MCC-4, the SP-1, 2, 3, and the CNS10-160B packagings, packaging costs were assumed to be about the same as those of a similar packaging. Thus, after cost data for fresh PWR and fresh BWR fuel packagings manufactured by Columbiana Hi Tech Front End, LLC were obtained by phone calls and email exchanges with a manufacturer's representative, packaging costs for the MCC-4 fresh PWR fuel packaging and for the SP-1, 2, 3 fresh BWR fuel packaging were assumed to be about the same as the costs of the PWR and BWR fresh fuel packagings manufactured by Columbiana Hi Tech Front End LLC. And because the size and design of the CNS10-160B packaging are similar to that of the RH-TRU 72B packaging, it was assumed that the cost of this packaging would be about the same as that of the RH-TRU 72B packaging.

Finally, the cost of one packaging was estimated assuming a cost of about $10.00/lb (in 2004 $) of packaging weight. Since Table O2-2 shows that the Paducah Tiger packaging weighs 21,030 lb, the cost was estimated to be about $210,300 in 2004 $, or $211,600 in 2007 $.

Rental Costs for Packagings Assumed to be Reused Many Times. Because they are more complex and relatively more expensive, all Type B packagings were assumed to be reused many times over the duration of their service lives, which were represented by a triangular distribution with low, modal, and high values of 1, 10, and 30 years. The median life was approximately 20 years. For these packagings, a daily rental cost was developed by performing a present value analysis. This analysis was performed using the discounted cash flow methods recommended by Higgins (2001). The purchase price was assumed to match the manufacturer's cost at a discount rate of 10%. Table O2-4 presents the parameters that were used in this analysis. The utilization factor represents the fraction of the days in a year the packagings are assumed to be in use. Instead of applying an overhead percent to the packaging purchase price, a nominal O&M cost ($10,000 in 2004 $, then escalated using the Consumer Price Index [CPI] for all items) was included in the analysis as a fixed cost. This assumes that the cost to test and maintain a packaging is independent of its size or weight. The analysis uses straight line depreciation based on the expected life of the packaging. For discounting purposes, year zero was assumed to be 2007. The first six parameters in Table O2-4 were assumed to be fixed. The final parameter, the useful life of the packaging, was assumed to vary stochastically. Values for this parameter were selected by random sampling from the triangular distribution for this parameter.

Table O2-4. Present value analysis parameters.

Fixed Parameters	Values			Units
Price of Reusable Items	CNS10-160B $725,000 RH-TRU 72B[a] $613,400 CHT-OP-TU $27,890 9975 $8,030			2007 $
Utilization Factor	0.90			Fraction
Inflation	3.0%			
Tax Rate	36.0%			
Discount Rate	10.0%			
O&M	$11,150			2007 $/year
Sampled Parameter	Low	Modal	High	
Useful Life	1	10	30	Years

[a] The RH-TRU 72B packaging consists of a welded canister and an overpack that is fitted with two impact limiters. Based on the costs of these items for SNF casks, the costs of the RH-TRU 72B canister and its overpack and impact limiters were estimated to be $111,600, $362,400, and $251,000 in 2007 $.

The present value analysis was run 10,000 times. For each simulation, the calculated cost was adjusted to return a zero net present value based on the sum of discounted cash flows for all years of the analysis. Figure O2-2 displays the results of the analysis as a series of rental costs sorted low to high. Because some consideration was given to using the interior canister of the RH-TRU 72B as a single use container, the rental costs for that packaging do not include the canister. When it is included, the daily rental cost is exactly the same as the CNS10-160B. The rental costs displayed in Figure O2-2 are for a shipment, not a single package. The CHT-OP-TU results are for 10 packages and the 9,975 results for 22.

Inspection of Figure O2-2 shows that rental costs increase very rapidly once cumulative fractions pass 0.90. This corresponds roughly to lifetimes dropping below about 5 years. Thus, the 90th percentile rental cost is $563/day for the CNS10-160B while the 99th percentile rental cost (corresponding to a 2-year life) is over $1,300/day. Also, the rental cost for 9975 does not vary strongly with the life of the packaging, but is driven instead by the maintenance costs. For an average life of 13 years, the daily rental cost for 22 packagings (a shipment) is $811, of which $731 is for maintenance and $80 is to recover the cost of the packaging. In contrast, of the $360 rental charge for the CNS 10-160B, the vast majority, $327, is for recovery of the packaging cost and only $33 is for maintenance.

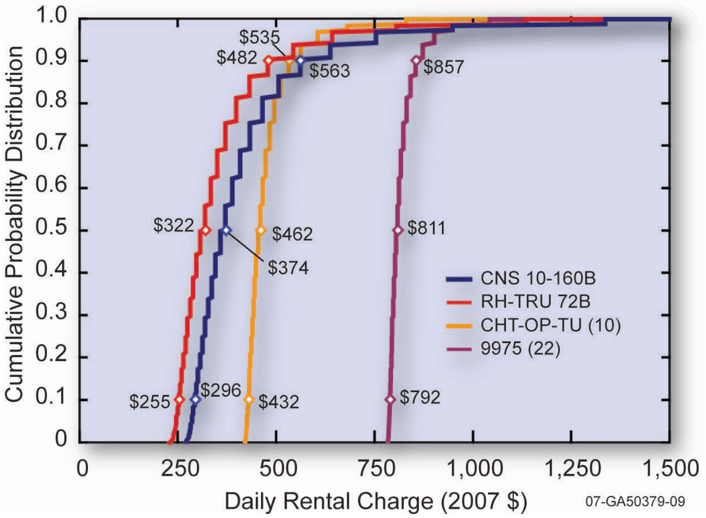


Figure O2-2. Cumulative distribution of daily rental costs for Type B packagings.

O2-6.3 RESULTS

Ten thousand sets of values for the 17 input parameters in the Cost Algorithm, for which distributions were developed, were selected by Monte Carlo sampling. Combination of each set of these values with the values specified for the 12 parameters that had single values generated 10,000 full sets of input for the Cost Algorithm. Running of the Cost Algorithm using these 10,000 sets of input allowed distributions for the five output parameters (Total Cost, Packaging Cost, Loading Cost, Shipping Cost, and Unloading Cost) to be constructed. Output was developed for single shipments of

- Yellow cake from the mills or ports of entry to regional facilities for conversion using the distribution of trip distances constructed for these shipment routes
- UF_6, enriched UF_6, depleted UF_6, depleted UO_2, UOX, TRU/TRUOX, TRU, FP, and U from regional facilities to regional facilities using the distribution of trip distances constructed for the routes that interconnect regional facilities
- Fresh PWR and BWR fuel assemblies from the regional facilities to the reactor sites using the distribution of trip distances taken from NUREG/CR-6672 for shipments of spent fuel from reactors to these six hypothetical regional facilities.

Monte Carlo sampling of parameters described by normal distributions or any other simple continuous algebraic formula is straightforward. The value of the independent variable in the algebraic formula is selected by Monte Carlo sampling, and then the value of the formula is used to calculate the value of the dependent variable. Selecting values for parameters represented by triangular distributions was done as follows. For any probability, P, the stochastic parameter, X, is calculated as

$$P \leq \text{Pmode}: X = \text{min} + \sqrt{P} \bullet (\text{max} - \text{min}) \bullet (\text{mode} - \text{min}) \tag{4a}$$

$$P > \text{Pmode}: X = \text{max} - \sqrt{(1 - P)} \bullet (\text{max} - \text{min}) \bullet (\text{max} - \text{mode}) \tag{4b}$$

where "X" stands for any of the parameters in Table O2-4 or for any other parameter represented by a triangular distribution,

P_{mode} = (mode – min)/(max – min). (5)

Max, *min*, and *mode* are the high, low, and modal values used to specify the triangular distribution (Newendorp 1975).

To simplify discussion of the results, the nine packagings are divided into two groups: The first group contains the four Type B packagings, for which rental costs were developed. The remaining five packagings, the Type A packagings, constitute the second group.

O2-6.3.1 TYPE B PACKAGES

Figures O2-3 through O2-6 present the distribution of shipment costs developed for each Type B package by the Monte Carlo calculations. Figure O2-3 shows that the median total cost for the CNS10-160B package is about $32,700, and costs range from about $15,000 to $60,000 per shipment. Figure O2-4 shows that for the median total cost for the RH-TRU 72B package is about $140,900, and costs range from about $125,000 to $180,000 per shipment. The RH-TRU 72B has an inner canister that was assumed to be used as a single-use container. If that were not done, the cost for the RH-TRU 72B would decrease by about $110,000—the cost of the inner container. It should be evident that for single use packagings (or packaging systems that have expensive single use components), total trip costs will be largely determined by the cost of the single use items. Figures O2-5 and O2-6 present similar data for the CHT-OP-TU and 9975 packages.

Figures O2-3 through O2-6 also present for the Type B packages the distributions of trip cost without the packaging costs. The distributions of "handling" cost (loading, shipping, and unloading) are quite similar for the CNS10-160B and the RH-TRU 72B because, the loading, en-route, and unloading costs differ significantly only in weight based (i.e., tonne-km based) shipping costs. If the RH-TRU 72B canister is used as a single use container, the difference between the "handling" costs (loading shipping and unloading) for the RH-TRU 72B would decrease by over $100,000. Figures O2-5 and O2-6 show that the cost for the CHT-OP-TU and 9975 packages are also similar and not dramatically different from the costs of the other two Type B packages.

Table O2-5 presents for the Type B packages median values for the total shipment cost and also for the packaging related costs (loading and unloading costs, and the en-route shipping costs) that sum to give the total cost. Also presented in this table is the fractional distribution of each cost component to the total cost, the average distance of each shipment, and the weight of the package contents. Finally, the cost per kilogram and the cost per tonne-km are provided.

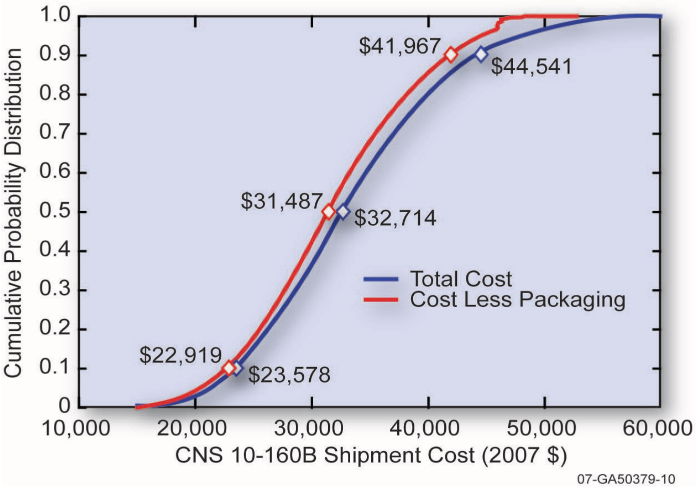


Figure O2-3. Cumulative distribution of shipment costs using a CNS10-160B package.

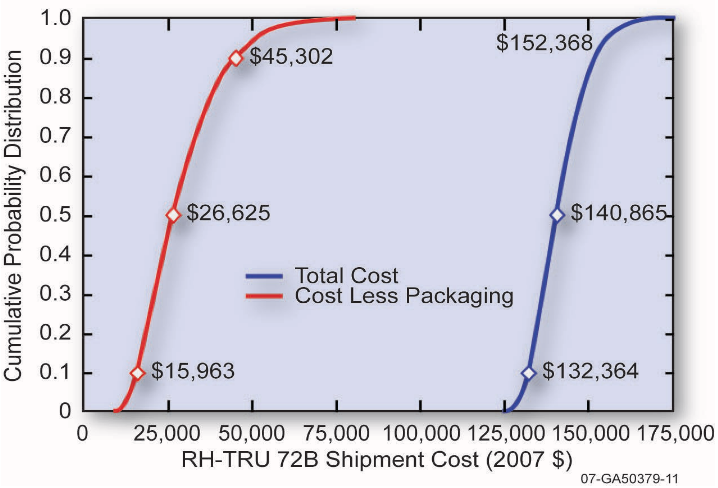


Figure O2-4. Cumulative distribution of shipment costs using a RH-TRU 72B package.

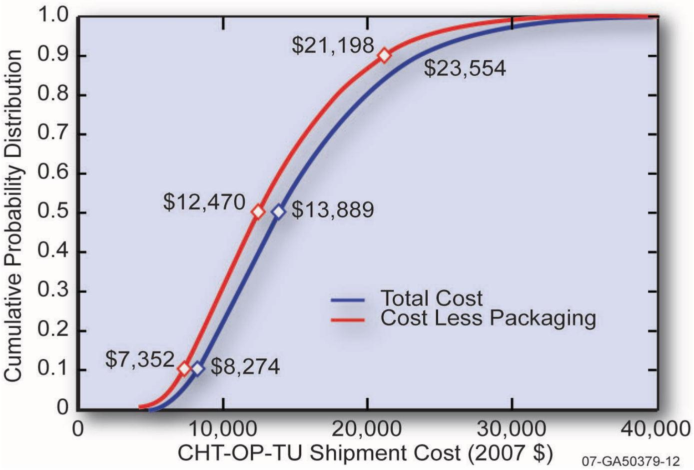


Figure O2-5. Cumulative distribution of shipment costs using a CHT-OP-TU package.

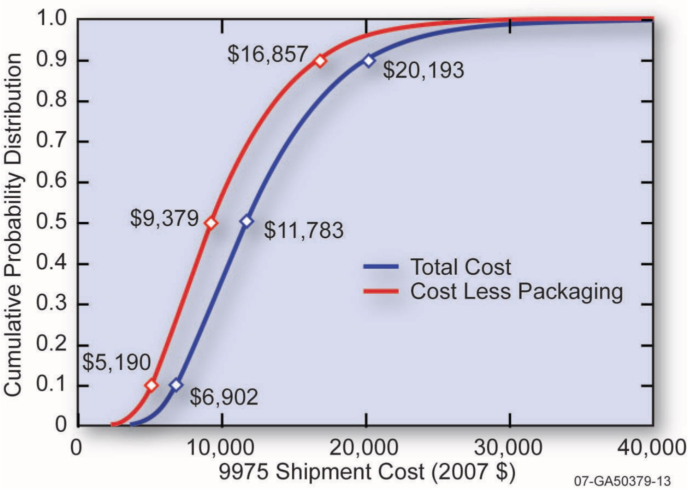


Figure O2-6. Cumulative distribution of shipment costs using a 9975 package.

Table O2-5. Package median shipment cost and other data for Type B packages.[a]

	CNS10-160B Regional Sites to Regional Sites		RH-TRU 72B Regional Sites to Regional Sites	
	Value (2007 $)	Fraction	Value (2007 $)	Fraction
Total Cost	$ 32,745	1.00	$ 140,853	1.00
Packaging	$ 1,228	0.04	$ 112,592	0.809
Shipping	$ 8,109	0.264	$5,084	0.037
Load/Unload	$ 21,354	0.696	$ 21,510	0.155
Distance	2,690 km		2,690 km	
Payload	**2.63 MT HM**		**1.475 MT HM**	
Unit Cost	$12.45/kg HM $4.63/MT-km		$95.49/kg HM $35.50/MT-km	
	CHT-OP-TU Regional Sites to Regional Sites		9975 Regional Sites to Regional Sites	
	Value (2007 $)	Fraction	Value (2007 $)	Fraction
Total Cost	$3,871	1.00	$11,794	1.00
Packaging	$1,418	0.103	$2,374	0.202
Shipping	$4,212	0.304	$900	0.077
Loading	$8,206	0.593	$8,488	0.722
Distance	2,690		2,690	
Payload	**10 × .643 MTHM**		**22 × 2 kg HM**	
Unit Cost	$2.16/kg HM $0.80/MT-km		$268.05/kg HM $99.65/MT-km	

a. The component values may not sum to the total cost. The actual medial values for the components usually do not exist in the case with the median total cost unless all are distributed similarly.

O2-6.3.2 TYPE A PACKAGES

Figures O2-7 through O2-9 present the distribution of shipment costs developed for each Type A package using the Monte Carlo method. In each case, the packaging is treated as being used only once. As a consequence, except for the 55-gallon drum, the total costs including packaging are dramatically different from the "handling" costs, that is, the costs without packaging costs. The cost of the 55-gallon drum is only about $100. The component of the rental costs devoted to O&M costs is about $30 per day. For a three to four-day shipment, the rental component due to O&M roughly equals the purchase price of the container, and a "single-use" approach is very reasonable. For the other packages, the case for single-use treatment is much less persuasive.

With the exception of the 55-gallon drum, the handling costs are quite similar—generally between about $7,000 and $25,000 per shipment. These values are also similar to the handling costs for the Type B packages. The implication is that shipment costs are primarily dependent on the cost of the packaging if it is single-use, as in the case of the Type A packages, but mostly dependent on the handling costs for the multiple-use packages, as in the case of the Type B packages.

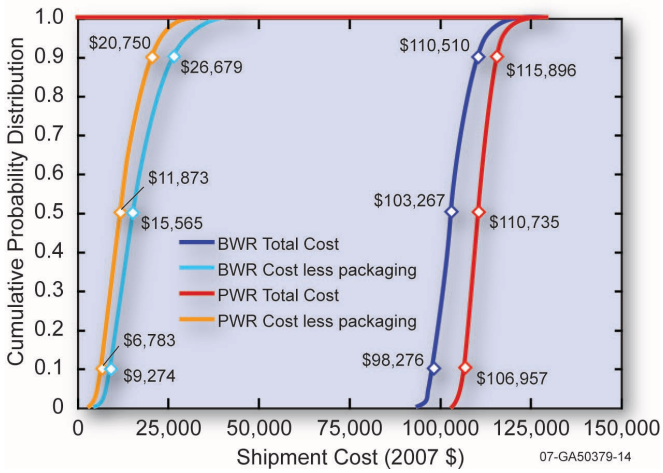


Figure O2-7. Cumulative distribution of shipment costs using an MCC-4 package (PWR fuel) or a SP-1, 2, 3 package (BWR fuel).

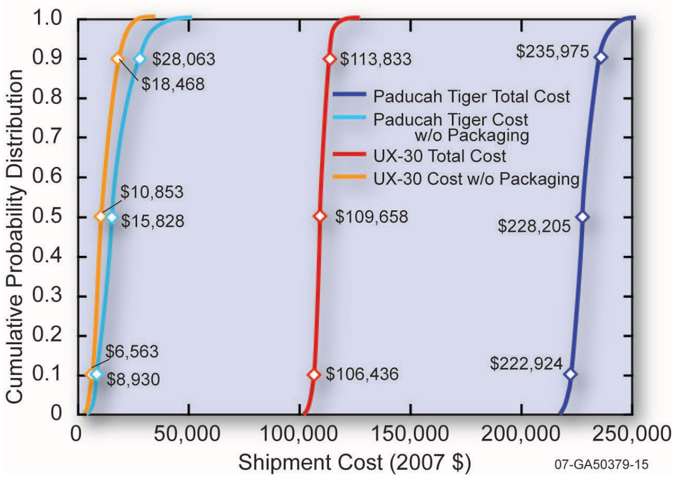


Figure O2-8. Cumulative distribution of shipment costs using a Paducah Tiger or a UX-30 package.

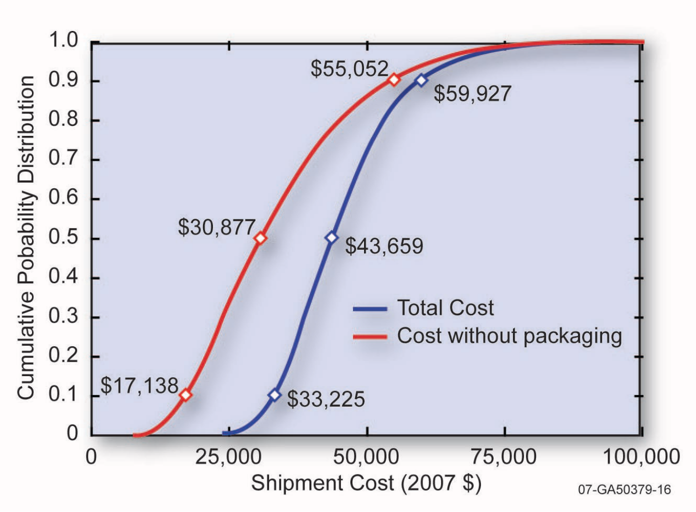


Figure O2-9. Cumulative distribution of shipment costs using a 55-gallon drum.

Table O2-6 presents for the Type A packages, median values for the total shipment cost and also for the packaging related costs, the loading and unloading costs, and the en-route shipping costs that sum to give the total cost. Also presented in this table is the fractional contribution of each cost component to the total cost, the average distance of each shipment, and the weight of the package contents. Finally, the cost per kilogram and the cost per tonne-km are provided.

O2-6.3.3 UNIT SHIPPING COSTS

Division of the average value for the total trip cost by the product of the average trip distance and weight of the contents of all packages shipped together in one shipment yields the value for the cost of shipping 1.0 tonne (1000 kg) of material 1.0 km. Table O2-7 presents these values for all the packages examined by this module. The table shows that the value of the shipping cost per tonne-km for the 9975 package is two orders of magnitude larger than the values for eight of the other nine packages. This very high cost per tonne per kilometer is caused by the low capacity—only 2 kg/package. Criticality generally limits the capacity to 4.5 kg of contained weapons grade plutonium. Other TRU may allow a higher capacity, but the content is limited to a heat generation rate of 19 Wand for TRU with higher isotopes, this will probably further limit the capacity. The 2 kg value used in this analysis is likely conservative.

Table O2-6. Median shipment cost (2007 dollars), and other data for Type A packages.

	SP-1,2,3 Regional Sites to Reactors		MCC-4 Regional Sites to Reactors	
	Value (2007 $)	Fraction	Value (2007 $)	Fraction
Total Cost	$103,247	1.0	$105,634	1.0
Packaging	$86,998	0.848	$11,734	0.882
Shipping	$779	0.008	$1,587	0.017
Load/Unload	$14,774	0.144	$4,851	0.090
Distance	2140 km		2140 km	
Payload	3 × 0.636 MTHM		2 × 1.15 MTHM	
Unit Cost	$54.11/kg HM $25.29/MTHM-km		$48.13/kg HM $22.49/MTHM-km	
	Paducah Tiger Regional Sites to Regional Sites		UX-30 Regional Sites to Regional Sites	
	Value (2007 $)	Fraction	Value (2007 $)	Fraction
Total Cost	$228,246	1.0	$109,668	1.0
Packaging	$211,583	0.930	$98,151	0.900
Shipping	$4,524	0.0120	$3,690	0.034
Load/Unload	$11,341	0.050	$7,178	0.066
Distance	2690 km		2690 km	
Payload	6.45 MTHM		4 × 1.54 MTHM	
Unit Cost	$22.79/kg HM $8.47/MTHM-km		$17.8/kg HM $6.62/MTHM-km	
	55-Gallon Drum Mills to Regional Sites			
	Value (2007 $)	Fraction		
Total Cost	$43,683	1.0		
Packaging	$11,484	0.271		
Shipping	$5,114	0.121		
Load/Unload	$12,592	0.609		
Distance	2550 km			
Payload	104 × 0.196 MT			
Unit Cost	$3.02/kg HM $1.19/MTHM-km			

O2-7. DATA LIMITATIONS

At present, there is very little data available on the estimated or actual costs of shipping low-level radioactive materials. Actual or estimated cost data for the shipments considered in this module are sparse because for many of the shipments examined one or both of the facilities between which the shipments would take place (e.g., reprocessing, recycled fuel fabrication, and interim decay storage facilities) do not exist, because reprocessing of SNF is currently not performed in the United States.

Table O2-7. Median package shipping cost.

Package	Cost per Shipment (2007$)	Cost per kilogram (2007 $)	Cost per tonne-km (2006 $)
55-gallon drum	$41,047	$2.013	$0.79
Paducah Tiger	$217,872	$22.79	$8.47
UX-30	$104,551	$11.46	$4.26
CHT-OP-TU	$12,679	$1.73	$0.645
9975	$10,229	$232.47	$86.43
CNS10-160B	$30,401	$4.61	$1.715
RH-TRU 72B	$27,548	$7.57	$2.797
MCC-4	$105,634	$45.86	$21.43
SP-1,2,3	$98,508	$51.63	$24.12

Because the packages and trucking infrastructure that would be used to ship the low-level radioactive materials that are considered by this module are already commercially available technologies, the shipping cost estimates developed in this module, though approximate, are not likely to be highly inaccurate. Thus, upper bound (downside) estimates of shipping costs should not be substantially larger than the central estimates developed in this module. However, lower bound (upside) estimates could be substantially smaller than the central estimates developed here if the nuclear fuel cycle becomes much larger in the future, whereupon substantial economies of scale might be achievable.

The cost estimates for the shipment of yellow cake assume that the cost per tonne of yellow cake at a North American mill is about the same as the cost per tonne when delivered by ship to a port of entry. The cost estimates developed in this module contain no costs for any capital facilities needed to load the low-level radioactive materials of concern into their shipment packages (e.g., for loading of the CNS10-160B or the RH-TRU 72B packages). It is assumed that either these costs are incorporated into the capital cost of the regional facility where these packages would be initially loaded or that these costs are not large enough to be significant. Finally, significant cost savings may be obtained if the packagings utilized and the equipment at the facilities to which these low-level radioactive materials are shipped should be designed to be mutually compatible. Once a full nuclear fuel cycle economic model has been developed, package/storage system costs should be reviewed to identify any significant cost savings that would result from the use of mutually compatible equipment designs.

O2-8. COST SUMMARIES

The module cost information is summarized in the What-It-Takes (WIT) cost summary in Table O2-8. The summary shows the reference cost basis (constant year $U.S.), the reference basis cost contingency (if known), the cost analyst’s judgment of the potential upsides (low end of cost range) and downsides (high end of cost range) based on references and qualitative factors, and selected nominal costs (judgment of the expected costs based on the references, contingency factors, upsides, and downsides). These costs are subject to change and are updated as additional reference information is collected and evaluated, and as a result of sensitivity and uncertainty analysis. Refer to Section 2.6 in the main section of this report for additional details on the cost estimation approach used to construct the WIT table.

Because the amounts of each low-level radioactive material generated per operating reactor per year will depend on the degree to which SNF is reprocessed and also on the reprocessing method (aqueous or electrochemical) used, annual shipping costs are highly scenario dependent. Consequently, no annual shipping costs are presented in this table, and no code-of-accounts table is presented. Once nuclear fuel cycle scenarios have been constructed, annualized costs for the shipment of low-level radioactive fuel cycle materials should be entered as an annualized O&M cost in any code-of-accounts table.

Table O2-8. What-It-Takes (WIT) Cost Summary Table – Based on Original Data (2006$)

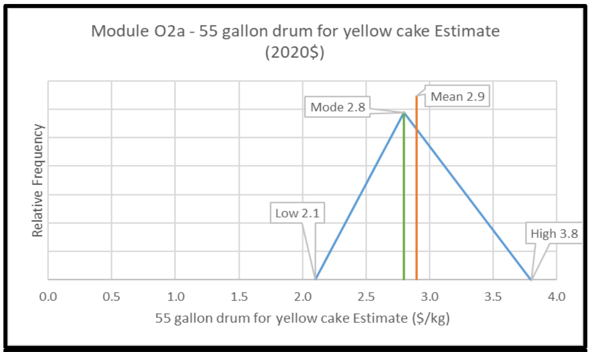
Package (Packaging and Contents)	Packages/ Shipment	Flow Streams from Table O2-1	Cost per kilogram of material for one fully loaded truck shipment		
			Upside (Low Cost)	Downside (High Cost)	Selected Value (Nominal Cost)
55-gallon drums for yellow cake	104	1	$1.54	$2.76	$2.01
Paducah Tiger for UF_6 or Depleted UF_6	1	2,5	$22.28	$22.79	$23.54
UX-30 for Enriched UF_6	4	3,4	$11.34	$12.09	$11.73
CHT-OP-TU for depleted UO_2, UOX or LLW	10	6,7,8	$1.23	$2.43	$1.73
9975 for TRU or TRUOX	22	9,13	$149.39	$355.41	$232.48
CNS10-160B for FP	1	10	$3.37	$6.26	$4.61
RH-TRU 72B for TRU or FP	1	12	$5.39	$10.53	$7.57
MCC-4 for fresh PWR fuel assemblies	2	14	$32.95	$35.59	$34.08
SP-1,2,3 for fresh BWR fuel assemblies	3	14	$49.18	$55.16	$51.63

The UFD evaluation does not analyze the same material covered in module O2. However, the update to this section is very straightforward. The original evaluation was based on Monte Carlo simulations of transportation of materials between fuel cycle facilities; the same fuel cycle facilities are the bases for the methodology for the update. The only parameters in the evaluation that have changed over time are the costs of the shipping packages. E-mail correspondence with shipping package suppliers were sufficient to determine that these costs have increased between 5% and 10% since the 2009 AFC-CBR; a conservative uniform factor of 10% will cover the spread. Thus, the updated table has values 10% higher than the previous version. This update will also round to the nearest tenth of a dollar ($0.1) for simplification

Table O2-9 What-It-Takes (WIT) Cost Summary Table – Updated for 2012 Shipping Package Costs (and also showing escalation to Year 2020$ (26% escalation from 2006 to 2020 per Escalation Table)

Package and Contents	Cost per kilogram of material for one fully-loaded truck shipment			
	Low Cost	Mode Cost	Mean Cost	High Cost
55-gal drum for yellow cake	$1.7	$2.2	$2.3	$3.0
Escalated to Yr 2020$	**$2.1**	**$2.8**	**$2.9**	**$3.8**
Paducah Tiger overpack for UF_6 or DUF_6 cylinder	$0.95	$1.05	$1.05	$1.16
Escalated to Yr 2020$	**$1.2**	**$1.3**	**$1.3**	**$1.5**
UX-30 for EUF_6	$12.5	$12.6	$12.8	$13.3
Escalated to Yr 2020$	**$15.7**	**$15.9**	**$16.1**	**$16.7**
CHT-OP-TU for DUO_2, UOX, or LLW	$1.4	$1.9	$2.0	$2.7
Escalated to Yr 2020$	**$1.8**	**$2.4**	**$2.5**	**$3.4**
9975 for TRU or TRUOX	$164.3	$255.7	$270.3	$391.0
Escalated to Yr 2020$	**$206.8**	**$321.8**	**$340.3**	**$492.1**
CNS10-160B for FP	$3.7	$5.1	$5.2	$6.9
Escalated to Yr 2020$	**$4.7**	**$6.4**	**$6.6**	**$8.7**
RH-TRU 72B for TRU or FP	$5.9	$8.3	$8.6	$11.6
Escalated to Yr 2020$	**$7.4**	**$10.4**	**$10.8**	**$14.6**
MCC-4 for PWR assemblies	$36.2	$37.5	$37.6	$39.1
Escalated to Yr 2020$	**$45.6**	**$47.2**	**$47.3**	**$49.2**
SP-1,2,3 for BWR assemblies	$54.1	$56.8	$57.2	$60.7
Escalated to Yr 2017$	**$68.1**	**$71.5**	**$72.0**	**$76.4**

These numbers also agree in most part with those in a 2008 GNEP study references below. Triangular distributions can be used to represent the uncertainty consistent with the above ranges.


Module O2a - 55 gallon drum for yellow cake Estimate (2020$)
Relative Frequency
Mode 2.8
Mean 2.9
Low 2.1
High 3.8
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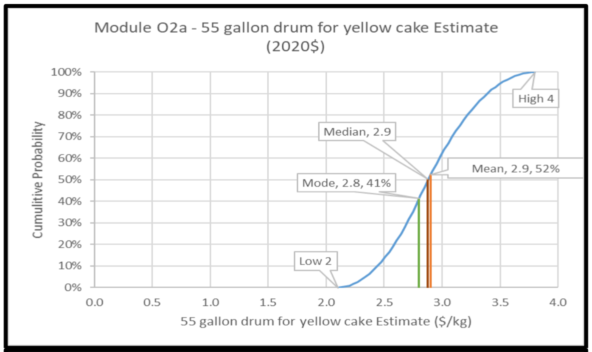
1.0
1.5
2.0
2.5
3.0
3.5
4.0
55 gallon drum for yellow cake Estimate ($/kg)


Module O2a - 55 gallon drum for yellow cake Estimate (2020$)
Cumulitive Probability
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
High 4
Median, 2.9
Mean, 2.9, 52%
Mode, 2.8, 41%
Low 2
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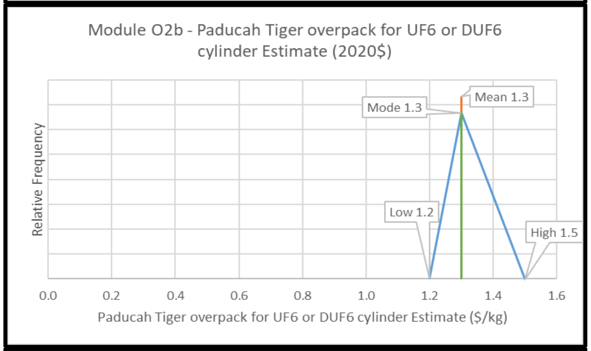
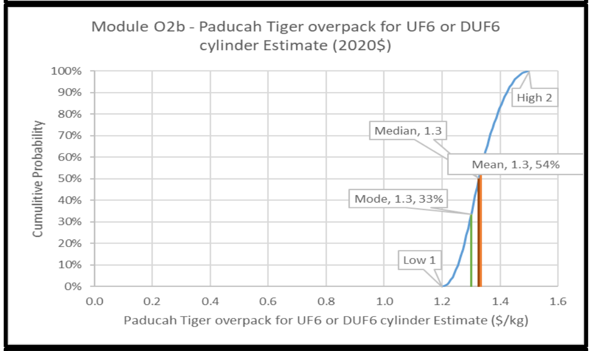
1.0
1.5
2.0
2.5
3.0
3.5
4.0
55 gallon drum for yellow cake Estimate ($/kg)


Module O2b - Paducah Tiger overpack for UF6 or DUF6 cylinder Estimate (2020$)
Relative Frequency
Mean 1.3
Mode 1.3
Low 1.2
High 1.5
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Paducah Tiger overpack for UF6 or DUF6 cylinder Estimate ($/kg)


Module O2b - Paducah Tiger overpack for UF6 or DUF6 cylinder Estimate (2020$)
Cumulitive Probability
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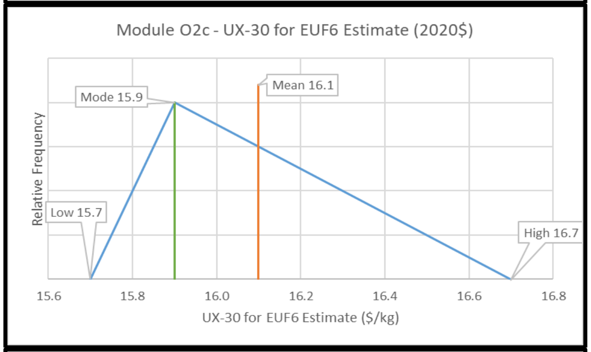
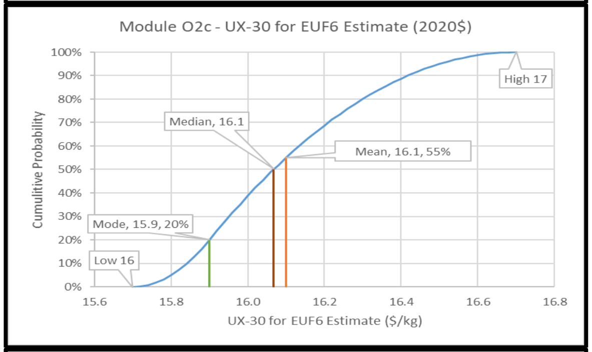
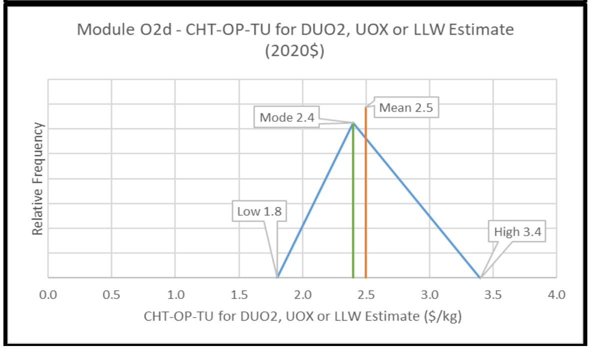
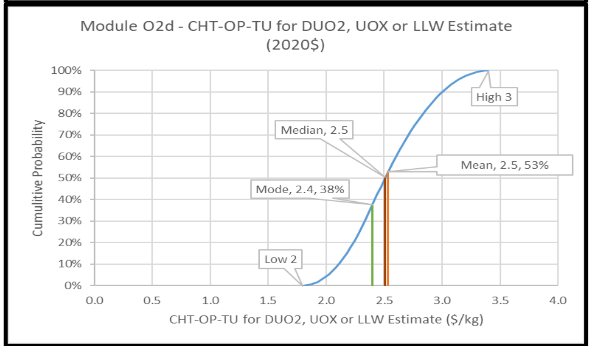
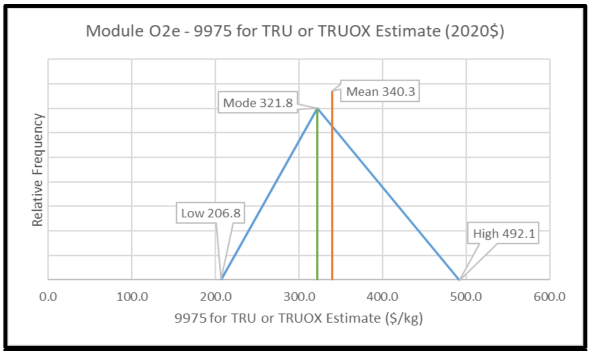
80%
70%
60%
50%
40%
30%
20%
10%
0%
High 2
Median, 1.3
Mean, 1.3, 54%
Mode, 1.3, 33%
Low 1
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Paducah Tiger overpack for UF6 or DUF6 cylinder Estimate ($/kg)

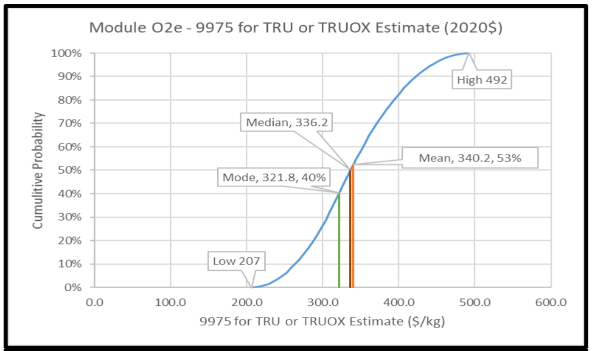

Module O2c - UX-30 for EUF6 Estimate (2020$)
Relative Frequency
Mode 15.9
Mean 16.1
Low 15.7
High 16.7
15.6
15.8
16.0
16.2
16.4
16.6
16.8
UX-30 for EUF6 Estimate ($/kg)

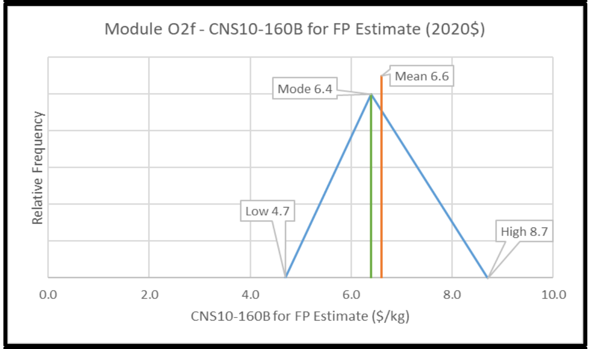

Module O2c - UX-30 for EUF6 Estimate (2020$)
Cumulitive Probability
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
High 17
Median, 16.1
Mean, 16.1, 55%
Mode, 15.9, 20%
Low 16
15.6
15.8
16.0
16.2
16.4
16.6
16.8
UX-30 for EUF6 Estimate ($/kg)

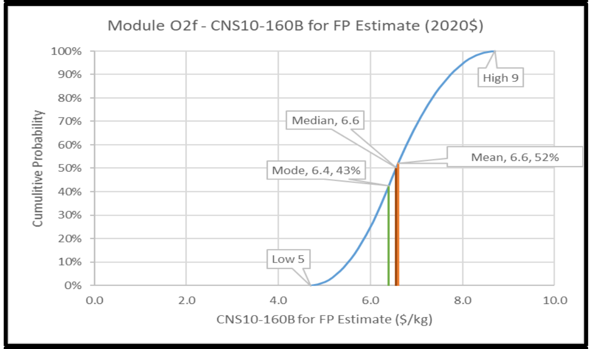

Module O2d - CHT-OP-TU for DUO2, UOX or LLW Estimate (2020$)
Relative Frequency
Mean 2.5
Mode 2.4
Low 1.8
High 3.4
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
CHT-OP-TU for DUO2, UOX or LLW Estimate ($/kg)

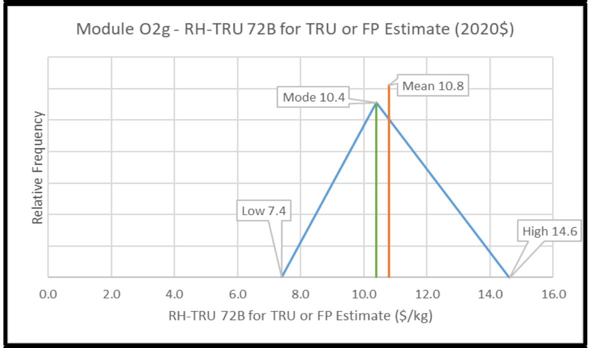

Module O2d - CHT-OP-TU for DUO2, UOX or LLW Estimate (2020$)
Cumulitive Probability
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
High 3
Median, 2.5
Mean, 2.5, 53%
Mode, 2.4, 38%
Low 2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
CHT-OP-TU for DUO2, UOX or LLW Estimate ($/kg)

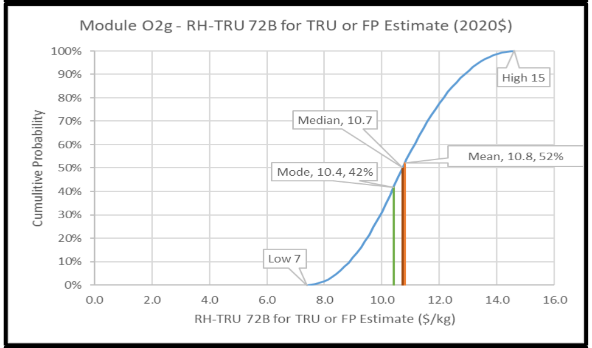

Module O2e - 9975 for TRU or TRUOX Estimate (2020$)
Relative Frequency
Mode 321.8
Mean 340.3
Low 206.8
High 492.1
0.0
100.0
200.0
300.0
400.0
500.0
600.0
9975 for TRU or TRUOX Estimate ($/kg)

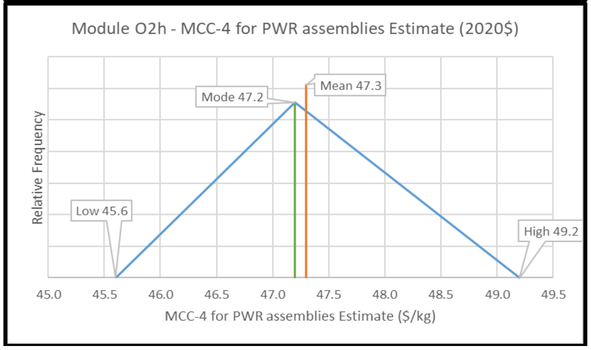

Module O2e - 9975 for TRU or TRUOX Estimate (2020$)
Cumlitive Probability
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
High 492
Median, 336.2
Mean, 340.2, 53%
Mode, 321.8, 40%
Low 207
0.0
100.0
200.0
300.0
400.0
500.0
600.0
9975 for TRU or TRUOX Estimate ($/kg)

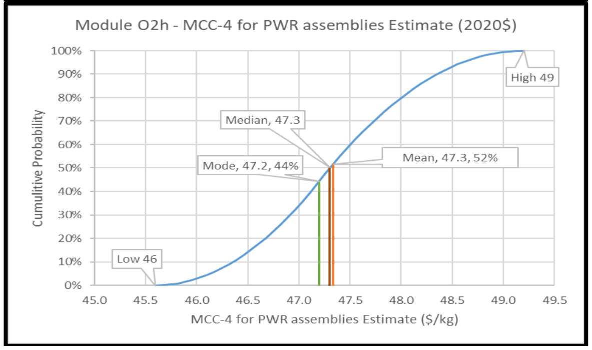

Module O2f - CNS10-160B for FP Estimate (2020$)
Relative Frequency
Mode 6.4
Mean 6.6
Low 4.7
High 8.7
0.0
2.0
4.0
6.0
8.0
10.0
CNS10-160B for FP Estimate ($/kg)


Module O2f - CNS10-160B for FP Estimate (2020$)
Cumlitive Probability
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
High 9
Median, 6.6
Mean, 6.6, 52%
Mode, 6.4, 43%
Low 5
0.0
2.0
4.0
6.0
8.0
10.0
CNS10-160B for FP Estimate ($/kg)


Module O2g - RH-TRU 72B for TRU or FP Estimate (2020$)
Relative Frequency
Mode 10.4
Mean 10.8
Low 7.4
High 14.6
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
RH-TRU 72B for TRU or FP Estimate ($/kg)


Module O2g - RH-TRU 72B for TRU or FP Estimate (2020$)
Cumlitive Probability
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
High 15
Median, 10.7
Mean, 10.8, 52%
Mode, 10.4, 42%
Low 7
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
RH-TRU 72B for TRU or FP Estimate ($/kg)


Module O2h - MCC-4 for PWR assemblies Estimate (2020$)
Relative Frequency
Mode 47.2
Mean 47.3
Low 45.6
High 49.2
45.0
45.5
46.0
46.5
47.0
47.5
48.0
48.5
49.0
49.5
MCC-4 for PWR assemblies Estimate ($/kg)


Module O2h - MCC-4 for PWR assemblies Estimate (2020$)
Cumlitive Probability
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
High 49
Median, 47.3
Mean, 47.3, 52%
Mode, 47.2, 44%
Low 46
45.0
45.5
46.0
46.5
47.0
47.5
48.0
48.5
49.0
49.5
MCC-4 for PWR assemblies Estimate ($/kg)

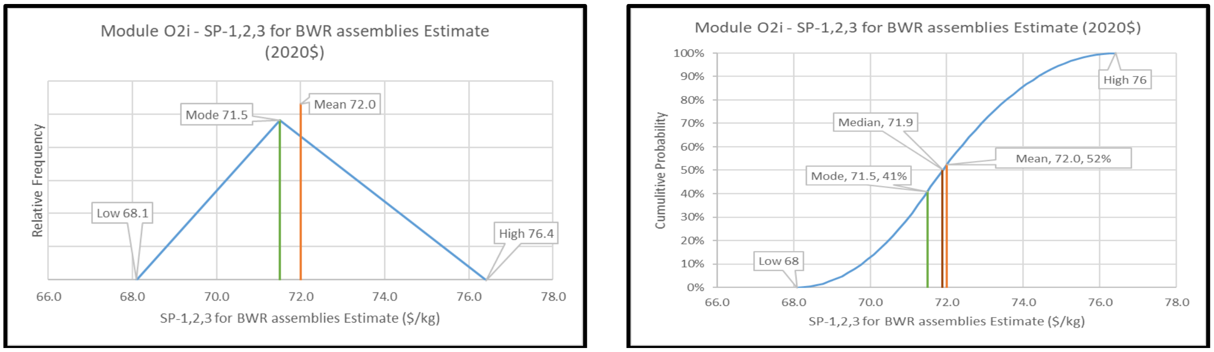


Figure O2-10. Probability frequency distribution and cumulative distribution of unit costs

O2-9. SENSITIVITY AND UNCERTAINTY ANALYSES

The analysis results presented above show that package trip costs depend strongly on the purchase price of single use packagings. For the five packagings that were assumed to be single-use items, the assumption that the packagings would be used only once is the principal determinant of trip costs. Consequently, trip costs would decrease substantially, if these packagings were reused several times. For example, the daily rental cost for the CNS10-160B packaging is about $275 per day if the service life of the packaging is 25 years, while if it is only 5 years then the packaging daily rental cost is about $500 per day. But, in either case, the rental cost for a trip of a few days is at least an order of magnitude less than the purchase price of the packaging.

Some states may try to levy a tariff on each shipment of low-level radioactive material that enters their state. These tariffs are not expected to be much larger than about $2,500 per state traversed, and because the average shipment of low-level radioactive material will traverse perhaps eight states, state tariffs should not exceed $20,000. Therefore, the state tariffs will constitute a minor component of total shipping costs. Finally, because shipping costs depend minimally on loading and unloading costs, none of the uncertainties associated with labor rates are important.

O2-10. REFERENCES

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Annex OX to Module O

Transportation Cost Methodology

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Annex OX to Module O
Transportation Cost Methodology

OX-1. COST ALGORITHM

This section formulates a general set of equations that specifies the total cost for a single shipment of a radioactive material from a point of origin to a destination. Terms in the set of equations are preceded by letters which indicate whether the value of the term is a single valued input quantity (i), a sampled input quantity (s), a quantity computed from other input (c), or a final output quantity (f). Each of the parameters used below is defined in Table OX-1, along with representative input values.

The total cost *(fTotalCost)* of a single radioactive material shipment is calculated as the sum of four costs:

1. The cost of the packages in which the radioactive material is shipped *(fPackCost)*
2. The costs associated with loading of the filled packages onto the shipment vehicles at the shipment origin *(fLCost*)
3. The en-route shipment costs *(fShipCost)*
4. The costs associated with unloading of the filled packages from the shipment vehicles at the shipment destination (*fUCost*).

Thus,

$$\text{fTotalCost} = \text{fPackCost} + \text{fLCost} + \text{fShipCost} + \text{fUCost}. \tag{6}$$

Packaging costs are calculated as the sum of the costs of the radioactive material container (e.g., an SNF canister), a container overpack, and overpack impact limiters. For single-use items (e.g., the canister), the item cost is the sum of the purchase cost and the procurement cost for the item; for reusable items, the item cost is the product of the daily rental cost of the item and the trip duration in days. Thus,

$$\text{fPackCost} = (\text{cNPack/Ship})[\text{sCanCost} + 2(\text{cDays})(\text{sOPCost} + \text{sILCost})] \tag{7}$$

where

cNPack/Ship = number of radioactive material packages carried by the shipment

2 (cDays) = round trip duration of the trip (the total number of days that the reusable cask components are rented) in days

sCanCost = cost of the single use radioactive material canister

sOPCost = rental costs per day of the canister overpack

sILCost = overpack impact limiters

As formulated, Equation 7 is directly applicable to a Type B package. For shipments in Type-A packages, if the container is reusable, then *sOPCost* is used to enter its rental cost, and if it is single-use, then *sCanCost* is used to enter its purchase cost.

The number of packages (*cNPack/Ship*) carried by the shipment is expressed as the product of the number of packages (*iNPack/Veh*) carried by a single package carrying shipment vehicle (truck or rail car) and the number of vehicles (*iNPackVeh*) in the train or the convoy of trucks that are carrying radioactive material packages. Thus,

$$\mathrm{cNPack/Ship} = (\mathrm{iNPackVeh})(\mathrm{iNPack/Veh}) \tag{8}$$

the one-way duration of the shipment in days (*cDays*) is calculated as the quotient of the trip length in kilometers (*sTrip*) and the average trip speed in kilometers per day (*sSpeed*). Thus,

$$\mathrm{cDays} = \mathrm{sTrip/sSpeed} \tag{9}$$

shipment loading costs (*fLCost*) are calculated as the sum of the wages for the loading crew, radiation technicians, and supervisors increased by an overhead factor (*sLHead*) with wages calculated as the product of the number of workers, an hourly rate, and the time required to load the packages onto the shipment vehicles (*cLDur/Ship*). Thus,

$$\mathrm{fLnCost} = (\mathrm{sLHead})(\mathrm{cLDur/Ship})[(\mathrm{sLS})(\mathrm{iNLS}) + (\mathrm{sLR})(\mathrm{iNLR}) + (\mathrm{sLC})(\mathrm{sNLC})] \tag{10}$$

where

sLS = hourly wages of the supervisors

sLR = hourly wages of the radiation technicians

sLC = hourly wages of the loading crew

iNLS = numbers of supervisors

iNLR = numbers of radiation technicians

iNLC = numbers of crew members.

Similarly, the shipment unloading costs (*fUCost*) are calculated using the following equation.

$$\mathrm{fUCost} = (\mathrm{sUHead})(\mathrm{sUDur/Ship})[(\mathrm{sUS})(\mathrm{iNUS}) + (\mathrm{sUR})(\mathrm{iNUR}) + (\mathrm{sUC})(\mathrm{sNUC})] \tag{11}$$

where all the terms have meanings analogous to those specified for the terms in Equation 10 for loading costs.

The time required to load (*cLDur/Ship*) all the vehicles in the train or the truck convoy that are carrying radioactive material packages is calculated as the product of the total number of radioactive material packages in the shipment (*cNPack/Ship*) and the loading time per package (*sLDur/Pack*). Thus,

$$\mathrm{cLDur/Ship} = (\mathrm{cNPack/Ship})(\mathrm{sLDur/Pack}) \tag{12}$$

similarly, for unloading,

$$\mathrm{cUDur/Ship} = (\mathrm{cNPack/Ship})(\mathrm{sUDur/Pack}). \tag{13}$$

The en-route shipping cost (fShipCost) is calculated as the sum of the vehicle rental costs, the weight-based shipping costs for the radioactive material packages, any charge for transporting the radioactive material by dedicated vehicles, and any fees charged by states for the passage of the radioactive material packages through their states. Thus,

$$\mathrm{fShipCost} = 2(\mathrm{cDays})(\mathrm{cNVeh})(\mathrm{sVehCost}) + (\mathrm{iNPackVeh})[(\mathrm{cTonnekm})(\mathrm{sTariff}) + \mathrm{sDedVeh} + (\mathrm{sStates})(\mathrm{sSFee})] \tag{14}$$

where

cNVeh and *iNPackVeh* = total number of vehicles (trucks, rail cars) and the number of package carrying vehicles (trucks, rail cars) used to carry out the shipment

VehCost = rental cost per vehicle per day

2 (cDays) = round trip duration of the trip (the total number of days that the shipment vehicles are rented) in days

cTonnekm and sTariff = number of metric tonne-km transported by the radioactive material shipment and the shipping cost per metric tonne-km

sDedVeh = charge for using dedicated vehicles to transport the radioactive material

sStates and sSFee = number of states traversed by the shipment and the average state fee per radioactive material package for trans-shipment of the packages through the state.

The total number of vehicles (trucks or rail cars) used to carry out the shipment (*cNVeh*) is calculated as the sum of the vehicles that carry the radioactive material packages plus any additional vehicles (escort vehicles, buffer cars) in the shipment consist. Thus,

$$cNVeh = iNPackVeh+iNBufVeh \tag{15}$$

where *iNPackVeh* and *iNBufVeh* are the number of package vehicles and the number of buffer plus escort vehicles in the shipment consist.

Finally, the number of metric tonne-km of weight (*cTonnekm*) carried by a single package vehicle is calculated as

$$cTonnekm = sTrip(iWtIL + iWtOP + iWtCan + iWtCanCont) \tag{16}$$

where

sTrip = trip distance

iWtIL, iWtOP, iWtCant, and *iWtCanCont* = weights of the overpack impact limiters, the overpack, the canister, and the canister contents.

Table OX-1. Cost algorithm parameters.

		Input			Calc'd			
Parameter	Description	S	TD	OD	IC	FR	Value	Ref
iCanCost sCanCost	Purchase cost single use canister ($)	X	 X				Type A: Table O2-2 Type B: $0.44/.55/.77	
cDays	One-way shipment duration (days)				X			
sDedVeh	Charge for shipment by dedicated vehicles ($)		X				Type B: $0/43K/86K	T
sILCost	Rental cost reusable impact limiters ($)			X				
sLC	Loading crew labor rate ($/hr)			X			Figure OX-1	
fLCost	Loading costs ($)					X		
sLDur/Pack	Loading time per package (hr/pkg)	X	 X				Type A: Table O2-2 Type B: 6/12/24 hr	S,O
cLDur/Ship	Loading time per shipment (hr)				X			
sLHead	Cost loading overhead factor		X				1.75/2.5/3	O
sLR	Loading radiation technician labor rate ($/hr)			X			Figure OX-1	
sLS	Loading supervisor labor rate ($/hr)			X			Figure OX-2	
iNBufVeh	No. of buffer and/or escort vehicles	X					Type A: 0 Type B: 3	

Table OX-1. (continued).

Parameter	Description	Input			Calc'd		Value	Ref
		S	TD	OD	IC	FR		
sNLC	Size loading crew		X				Type A: 4/6/10 Type B: 6/10/12	S,O
iNLR	No. of loading radiation technicians	X					Type A: 1 Type B: 2	STS
iNLS	No. of loading supervisors	X					1	STS
cNPack/ Ship	No. packages/ shipment				X			
iNPackVeh	No. of vehicles that carry packages	X					1	
iNPack/Veh	No. packages/ vehicle	X					Type A: Table O2-2 Type B: 1	
sNUC	Size unloading crew		X				Type A: 4/6/10 Type B: 6/10/12	S,O
iNUR	No. of unloading radiation technicians	X					Type A: 1 Type B: 2	STS
iNUS	No. of unloading supervisors	X					1	STS
cNVeh	Total No. of vehicles used to perform shipment				X			
sOPCost	Rental cost reusable overpack ($/day)			X				
fPackCost	Package cost ($)					X		
sSFee	State fee ($)	X	X				Type A: $0 Type B:0/2500/5000	T
fShipCost	En-route shipping costs ($)					X		
sSpeed	Shipment speed (km/day)			X			1222.6/1800/2113.7	S,O
sStates	No. of states traversed			X				
sTariff	Cost per tonne-km ($/tonne-km)			X			$0.06/0.075/0.10	S,O
cTonnekm	Tonne-km per shipment				X			
fTotalCost	Total trip cost ($)					X		
sTrip	Shipment distance (km)			X				
sUC	Unloading crew labor rate ($/hr)			X			Figure OX-1	
fUCost	Unloading costs ($)					X		
sUDur/Pack	Unloading time per package (hr/pkg)		X				Type A: Table O2-2 Type B: 6/12/24 hr	S,O
cUDur/Ship	Unloading time per shipment (hr)				X			
sUHead	Cost unloading overhead factor		X				1.75/2.5/3	O
sUR	Unloading radiation technician labor rate ($/hr)			X			Figure OX-1	
sUS	Unloading supervisor labor rate ($/hr)			X			Figure OX-2	
iVehCost sVehCost	Vehicle rental cost ($)	X	X				Type A: in sTariff Type B: 1K/2K/5K	
iWtCan	Weight canister (tonne)	X					Type A: Table O2-2 Type B: 18 MT	
iWtCan Cont	Weight canister contents (tonne)	X					Type A: Table O2-2 Type B: 22 MT	
iWtOP	Weight overpack (tonne)	X					70 MT	

Table OX-1. (continued).

Parameter	Description	Input			Calc'd		Value	Ref
		S	TD	OD	IC	FR		
iWtIL	Weight overpack impact limiters (tonne)	X					17 MT	
Parameter Types	S = Single value input TD = Triangular distribution input OD = Other distribution input				IC = Intermediate calculated value FR = Final result			
References	S = Sandia Shipping Staff O = Shipping staff at other governmental laboratories				STS = Sandia Technical Staff T = Shipments of materials from TMI			

OX-2. LABOR RATES

OX-2.1 HOURLY LABOR WAGE (SLR, SUR, SLC, AND SUC)

Figure OX-1 below shows U.S. Bureau of Labor Statistics distributions of hourly take-home wage for representative skilled nonexempt occupations under which loading or unloading labor might fall (Bureau of Labor Statistics 2006). Included in this figure is a line that represents the amalgamation of the U.S. Bureau of Labor Statistics on the premise that all shown categories are equally likely. Because the hourly take-home wage for radiation technicians should be similar to that for operating engineers, this amalgamated labor rate distribution was assumed to apply not only to members of the loading crew but also to radiation technicians

OX-2.2 HOURLY OVERSIGHT WAGE (SLS, SUS)

Figure OX-2 shows U.S. Bureau of Labor Statistics distributions of take-home wage for selected technical occupations under which loading or unloading oversight might fall (Bureau of Labor Statistics 2006). Included in this figure is a line that represents the amalgamation of the U.S. Bureau of Labor Statistics on the premise that all shown categories are equally likely.

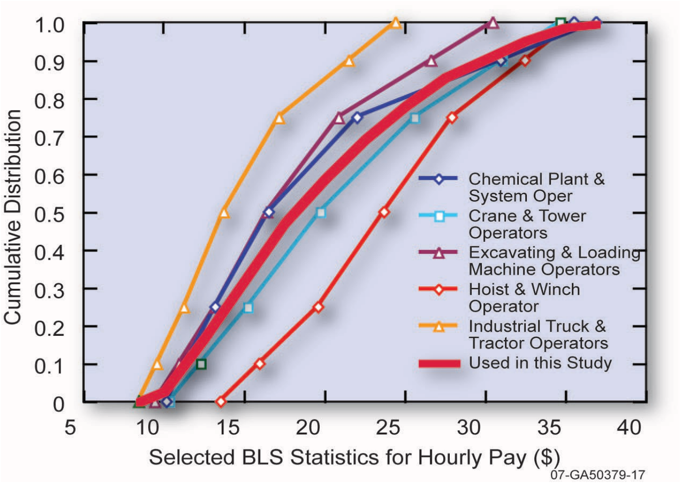


Figure OX-1. Hourly labor wage (Bureau of Labor Statistics 2006).

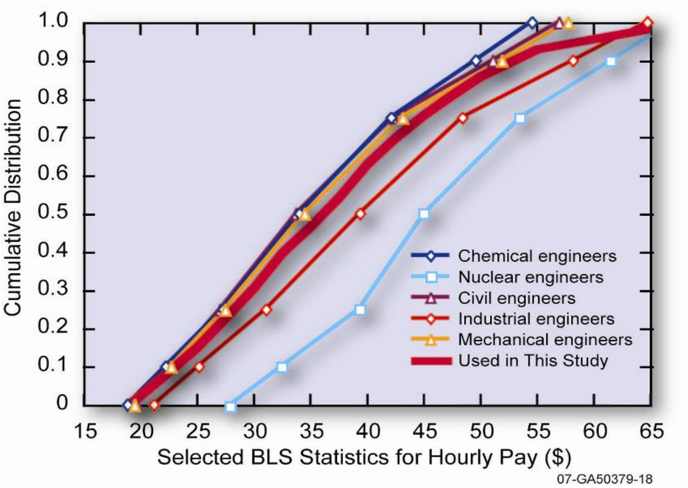


Figure OX-2. Hourly oversight wage (Bureau of Labor Statistics 2006).

OX-3. TRIP ONE-WAY DISTANCES (sTrip)

OX-3.1 Shipments by Rail

Three distributions of shipment distances were used to develop the transportation cost estimates presented in this module. The first distribution assumed that the number of operating reactors in the fuel cycle would not be much increased over the current number of operating reactors. For this scenario, no fuel reprocessing occurs and SNF is shipped directly from operating reactor sites to a permanent repository located at Yucca Mountain. The second and third distributions assumed:

- The number of operating reactors in the fuel cycle would be much larger than the current number
- SNF would be shipped to regional sites for interim storage or reprocessing
- MOX fuel fabricated at regional fuel fabrication facilities would be shipped back to operating reactor sites
- Vitrified HLW generated by reprocessing would be shipped to regional monitored retrievable storage sites.

This scenario uses two trip distance distributions. Both of these distributions assumed that one regional facility would be located in the north western, the north central, the north eastern, the south western, the south central, and the south eastern portions of the continental United States. Table OX-2 presents the hypothetical locations of these six regional sites.

For the first scenario, which covers shipments from operating reactors to Yucca Mountain, distance estimates published in the Yucca Mountain environmental impact statement (DOE 2002) were used to construct the distribution of possible trip distances. The second scenario used the trip distance distribution that was developed in NUREG/CR-6672 (Sprung et al. 2000), assuming SNF shipments from currently operating reactors to the six regional sites listed in Table OX-2. For the third scenario, which covers shipments between regional facilities, the Transportation Routing Analysis Geographic Information System (TRAGIS) routing code (Johnson and Michelhaugh 2003) was used to identify the shortest mainline rail route that connected each of these 15 origin/destination pairs that can be generated from the six hypothetical regional site locations listed in Table OX-2 and to calculate the lengths of these routes. Figure OX-3 depicts the routes identified by these TRAGIS calculations.

Because the six regional site locations listed in Table OX-2 are only hypothetical, the set of 15 distances calculated by TRAGIS was treated as a representative sample drawn from the "true" but presently "unknown" distribution of real distances between the locations of future regional sites. Because a reprocessing and a vitrification facility might both be located at the same regional site, a trip distance of 0 km was also assumed to be possible.

Table OX-2. Hypothetical locations for regional facilities.

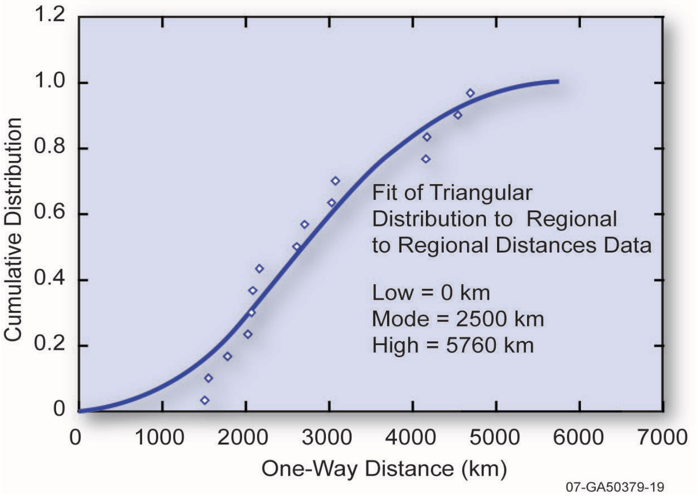
Region	Location
North Western	Hanford, WA
North Central	Prairie Island Indian Reservation, MN
North Eastern	West Valley, NY
South Western	Yucca Mountain, NV
South Central	Kay County, OK
South Eastern	Savannah River, SC

Figure OX-3. Mainline rail routes calculated using TRAGIS that connect the six hypothetical locations for regional facilities.

Low, modal, and high values for a triangular distribution of trip distances between future regional sites were selected as follows. First, the low value of the triangular distribution was set equal to zero to accommodate the possibility that a reprocessing facility and a vitrification plant might both be located at the same regional site. Then, the fifteen trip distances were rank ordered and modal and high values for the triangular distribution were selected that minimized the sum of the squares of the differences between the values of the fifteen representative distances and values of these distances on the cumulative distribution of trip distances generated from the triangular distribution.

Figure OX-4 presents the cumulative distribution that was generated by this minimization method with the restriction that the cumulative distribution passes through the point (0,0). Also plotted in Figure OX-4 are the 15 trip distances that were used to construct the triangular distribution and the low, modal, and high values of the triangular distribution that underlies the cumulative distribution.

Figure OX-5 plots all three of the trip distance distributions. Inspection of Figure OX-5 shows that the three distance distributions are quite similar. Thus, given the somewhat uncertain identities of many of the route origins or destinations, the differences in the three distributions are not very significant.



Source: Cask Shipment RevX.xls

Figure OX-4. Fit of region to region rail distance data to triangular distributions.

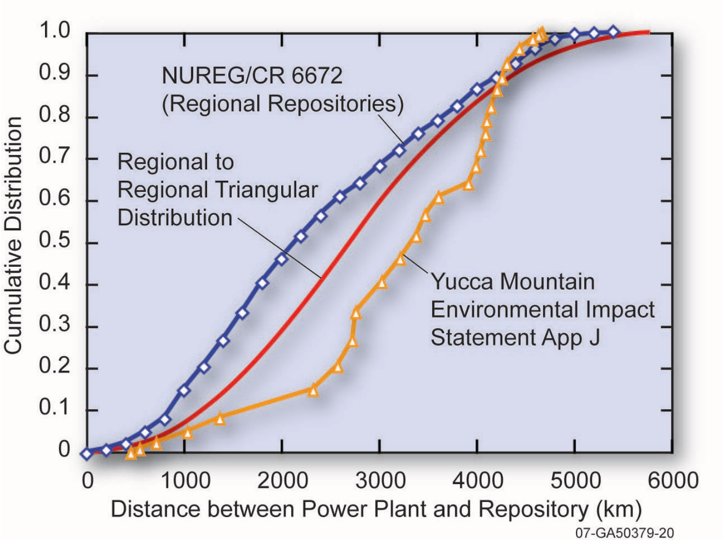


Figure OX-5. Distribution of trip distances (sTrip) for rail shipments from reactors to Yucca Mountain and for shipments to regional storage facilities.

OX-3.2 Shipments by Truck

Three distributions of shipment distances were used to develop the transportation cost estimates presented in this module. The three distributions assume that the number of operating reactors in the fuel cycle will be much larger than the current number and therefore that low-level radioactive material will be shipped to regional facilities for conversion, fabrication, recycling, or interim storage. The first distribution assumes that yellow cake will be shipped to regional conversion facilities from uranium mines located near Moab, Utah or from two representative ports of entry, Long Beach, California, and Norfolk, Virginia, if imported from overseas. The second distribution assumes that shipments between conversion, fabrication, recycling, or interim storage facilities will all be shipments between the regional facilities. Both of these distributions assumed that one regional facility will be located in the north western, north central, north eastern, south western, south central, and south eastern portions of the continental United States. The third distribution assumes that the fresh fuel fabricated at the regional facilities will be shipped to operating reactors.

For shipments of fresh fuel from regional fuel fabrication facilities to reactor sites, the distribution of route lengths used was the distribution developed in NUREG/CR-6672 (Sprung et al. 2000) for the shipment of spent fuel from reactor sites to the six hypothetical regional sites listed in Table OX-2. For yellow cake shipments or for shipments between regional facilities, the TRAGIS routing code (Johnson and Michelhaugh 2003) was used to identify shipping routes and to calculate their route lengths as restricted by the routing rules for Highway Route Controlled Quantities of Radioactive Materials. The 18 shipment routes selected by TRAGIS, which connect the uranium mines near Moab, Utah, and the ports of Long Beach, California, and Norfolk, Virginia, to the six hypothetical regional conversion facilities, are plotted in Figure OX-6. The 15 shipment routes selected by TRAGIS, that interconnect the six hypothetical regional site locations, are plotted in Figure OX-7.

Because the six regional site locations listed in Table OX-2 are only hypothetical, the set of 18 yellow cake shipment distances calculated by TRAGIS was treated as a representative sample drawn from the "true" but presently "unknown" distribution of real distances between uranium mines or port facilities and the locations of the six hypothetical future regional sites. A triangular distribution for the 18 trip distances was constructed as follows. First, the 18 trip distances were rank ordered. Then low, modal, and high values for a triangular distance distribution were selected. These values minimized the sum of the squares of the differences between the values of the 18 representative distances and values of these distances on the cumulative distribution (the integral of the triangular distribution) of trip distances generated from the triangular distribution (Newendorp 1975). Figure OX-8 presents the cumulative distribution of yellow cake shipment distances that was generated by this minimization method. Also plotted in Figure OX-8 are the eighteen trip distances that were used to construct the triangular distribution and the low, modal, and high values of the triangular distribution that underlies the cumulative distribution.

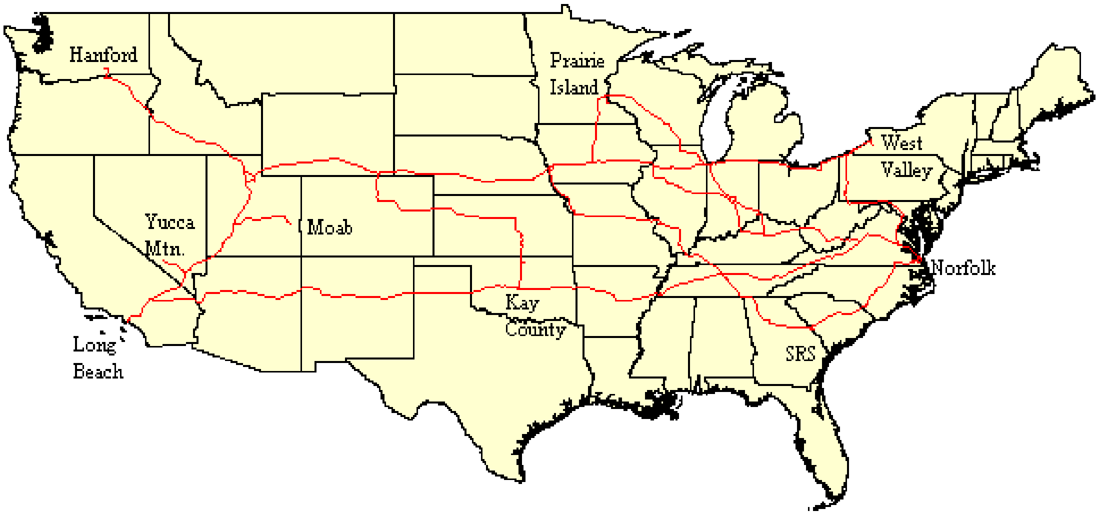


Figure OX-6. Truck routes calculated using TRAGIS that connect the yellow cake shipment sites to the six hypothetical locations for regional facilities.

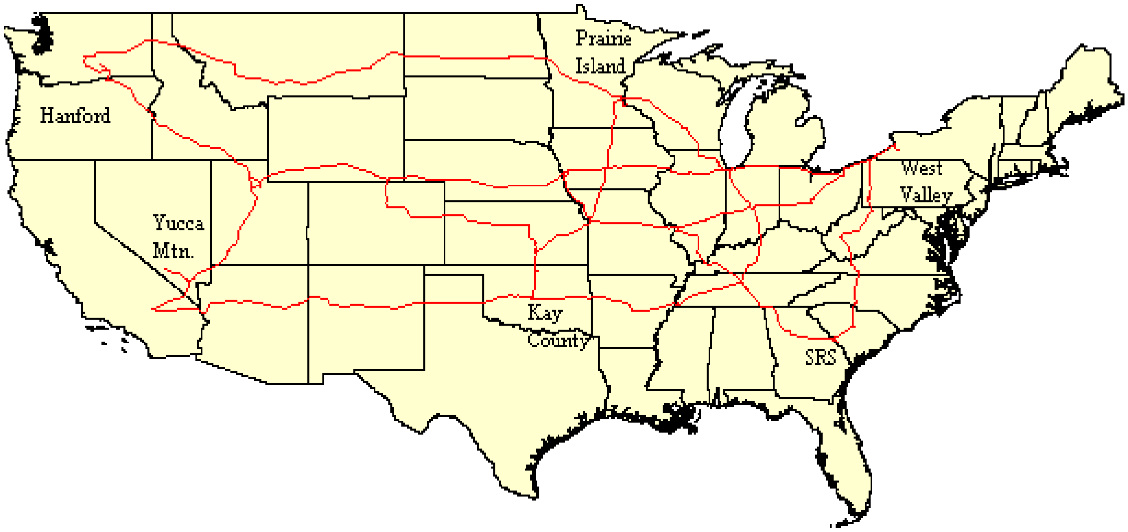


Figure OX-7. Truck routes calculated using TRAGIS that connect the six hypothetical locations for regional facilities.

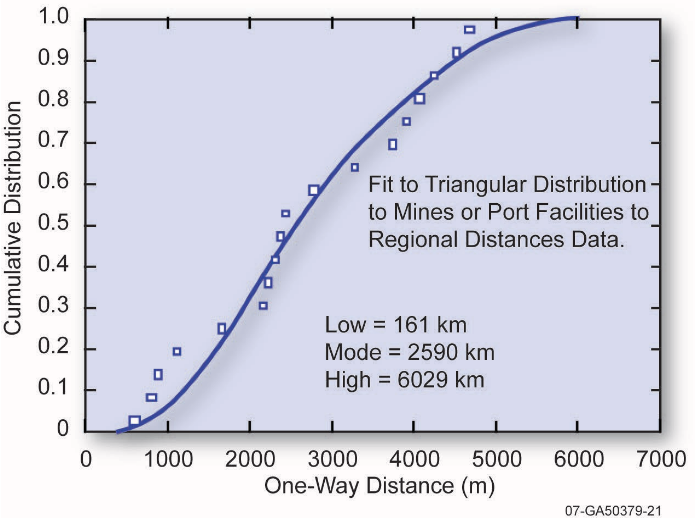


Figure OX-8. Cumulative distribution fit to the 18 route lengths that connect uranium mines in Moab, Utah, or the Long Beach, California, and Norfolk, Virginia, ports of entry to the six hypothetical regional facility sites.

The minimization analysis was also applied to the 15 shipment routes selected by TRAGIS that interconnect the six hypothetical regional site locations. However, because a conversion, fabrication, recycling, or interim storage facility might both be located at the same regional site, a trip distance of 0 km was also assumed to be possible. Therefore, the cumulative distribution generated by the minimization analysis was forced to pass through zero. Figure OX-9 presents the cumulative distribution that was generated by the minimization analysis with the restriction that the cumulative distribution passes through the point (0, 0). Also plotted in Figure OX-9 are the 15 trip distances that were used to construct the triangular distribution and the low, modal, and high values of the triangular distribution that underlies the cumulative distribution.

Figure OX-10 plots all three trip distance distributions. Inspection of Figure OX-10 shows that the three distance distributions are quite similar. Thus, given the somewhat uncertain identities of many of the route origins or destinations, the differences in the three distributions are not very significant.

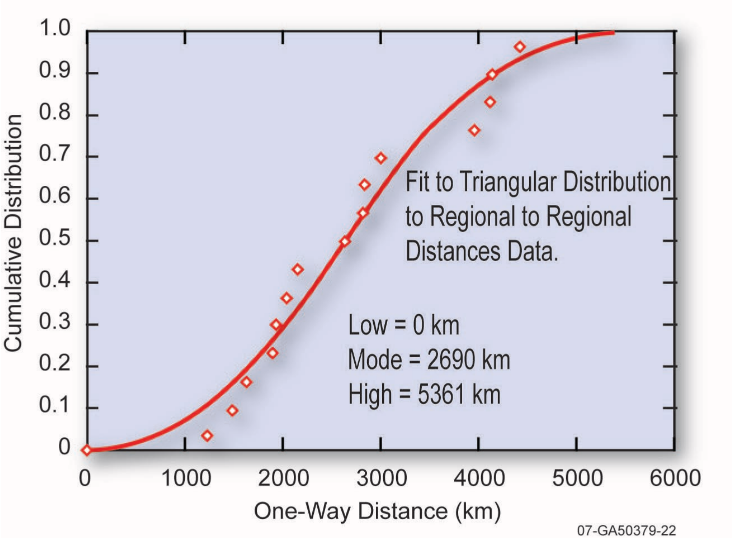


Figure OX-9. Fit of region to region truck distance data to triangular distribution.

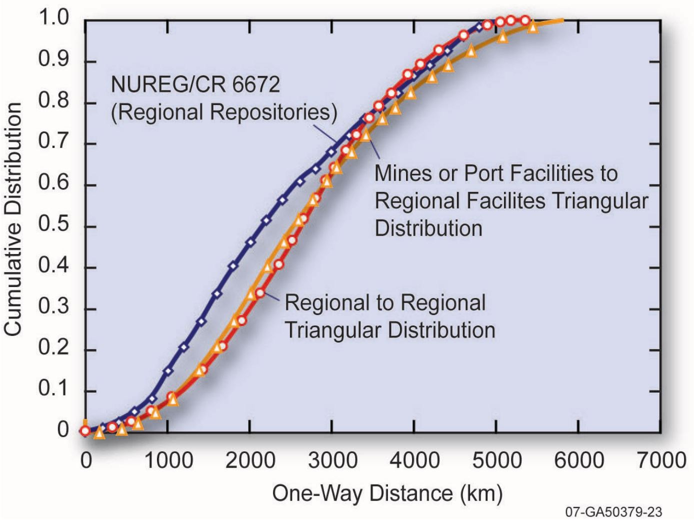


Figure OX-10. Cumulative distribution of trip distances (sTrip) for shipments from regional facilities.

OX-4. STATES TRAVERSED (sStates)

The TRANSCOST database (Michelhaugh 2002) includes a significant amount of information on routes between existing DOE facilities. These data include both route lengths and the states crossed by each route for more than 1,150 routes. Figure OX-11 presents a plot of these data.

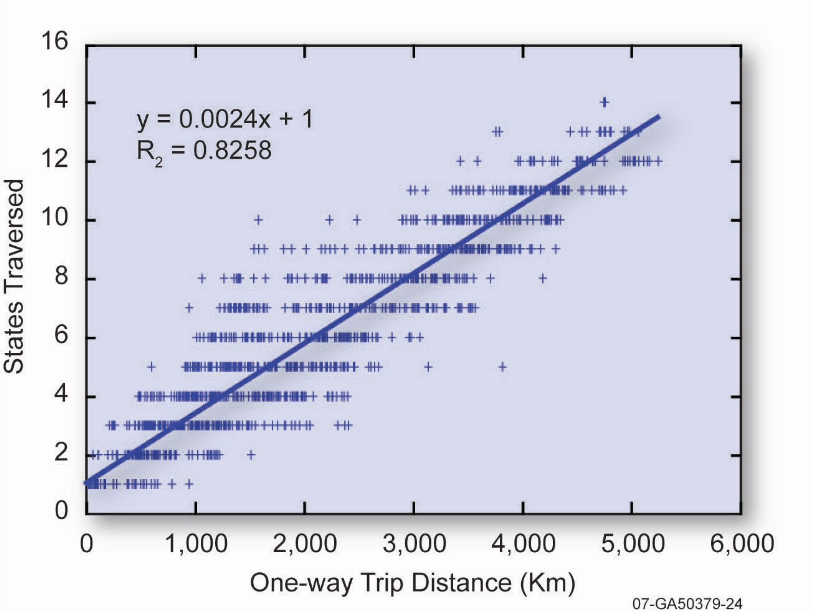


Figure OX-11. States traversed vs. trip distance.

As Figure OX-11 shows, the TRANSCOST data are well represented by the following linear relationship,

$$sStates_{av} = 0.0024\ sTrip + 1.00. \qquad (17)$$

Because of the scatter in the data, the standard error (SE_y) of this linear relationship is $SE_y = 1.25$. Nevertheless, despite the scatter in the data, the linear relationship has a surprisingly strong correlation coefficient of $R^2 = 0.8258$.

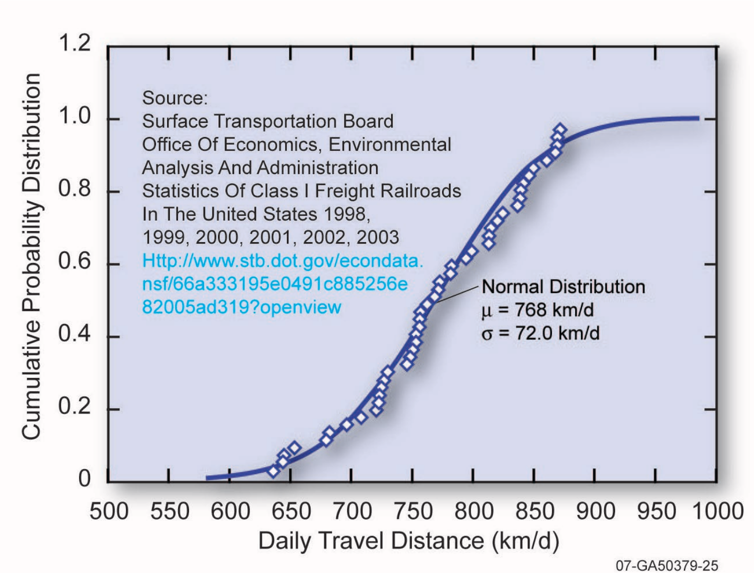
For the Monte Carlo calculation of trip costs, the estimate of sStates was taken as the random variate of a normal distribution using the linear relation for $sStates_{av}$ as a function of distance as the mean value of this distribution and the value of SE_y as its standard deviation. Thus,

$$sStates = (N|\ sState_{av},\ SE_y). \qquad (18)$$

OX-5. SHIPMENT SPEED (sSpeed)

OX-5.1 Shipments by Rail

Train speeds are based on data collected by the Surface Transportation Board, successor to the Interstate Commerce Commission (U.S. Department of Commerce 1998–2003). The Surface Transportation Board collects total train miles and road service hours, which includes time in switching yards and sidings. The quotient of these two yields an average speed that includes the delays inherent in normal commercial railroad freight traffic. Data were available for 6 years for each different rail freight company operating in the contiguous United States. The number of companies dropped from ten to six over the 5-year period, but averaged eight. The resulting 48 data points are plotted in Figure OX-12. As Figure OX-12 shows, these points are well fit by a normal distribution with a mean of 768 km/day and a standard deviation of 72.0 km/day.



Source: Cask Shipment RevX.xls

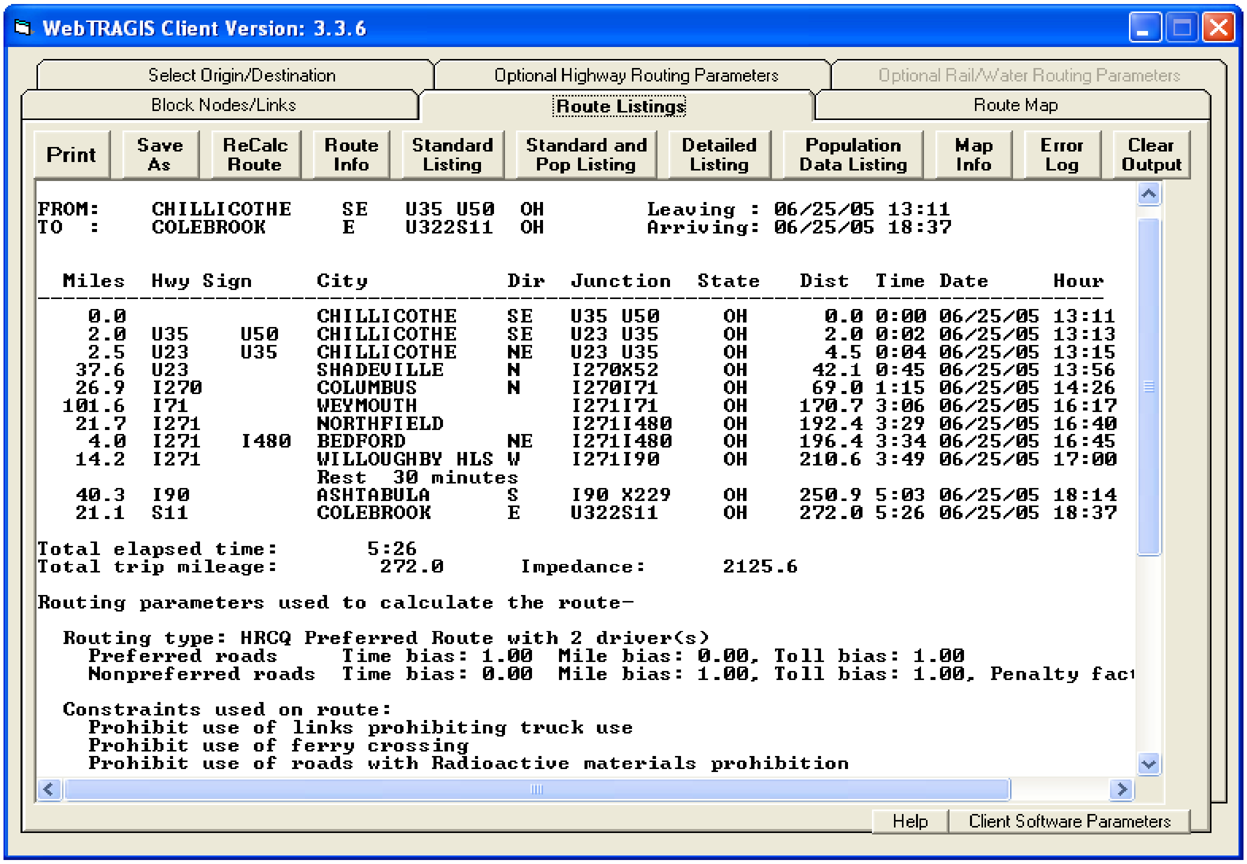
Figure OX-12. Estimating train speeds.

The standard deviation of the sample presented in Figure OX-12 represents the variability of a set of averages. The actual deviation of the full population has been lost. To account for the wider variability of the full population, the estimates of sSpeed used in the Monte Carlo trip cost calculation were calculated using three times the standard deviation of the normal distribution that was fit to the data in Figure OX-12.

$$\text{sSpeed} = (N|x_{av} = 768,\ s = 216) \tag{19}$$

OX-5.2 Shipments by Truck

Truck speeds are based on data collected by the TRAGIS routing code (Johnson and Michelhaugh 2003). Figure OX-13 shows an example of the TRAGIS Standard Listing output. The figure shows that TRAGIS provides estimates of driving time and driving distances for each trip route segment.



```
FROM:    CHILLICOTHE    SE   U35 U50  OH        Leaving : 06/25/05 13:11
TO  :    COLEBROOK      E    U322S11  OH        Arriving: 06/25/05 18:37


  Miles  Hwy Sign    City           Dir  Junction  State   Dist  Time Date      Hour
------------------------------------------------------------------------------------
    0.0              CHILLICOTHE    SE   U35 U50     OH       0.0 0:00 06/25/05 13:11
    2.0  U35    U50  CHILLICOTHE    SE   U23 U35     OH       2.0 0:02 06/25/05 13:13
    2.5  U23    U35  CHILLICOTHE    NE   U23 U35     OH       4.5 0:04 06/25/05 13:15
   37.6  U23         SHADEVILLE     N    I270X52     OH      42.1 0:45 06/25/05 13:56
   26.9  I270        COLUMBUS       N    I270I71     OH      69.0 1:15 06/25/05 14:26
  101.6  I71         WEYMOUTH            I271I71     OH     170.7 3:06 06/25/05 16:17
   21.7  I271        NORTHFIELD          I271I480    OH     192.4 3:29 06/25/05 16:40
    4.0  I271   I480 BEDFORD        NE   I271I480    OH     196.4 3:34 06/25/05 16:45
   14.2  I271        WILLOUGHBY HLS W    I271I90     OH     210.6 3:49 06/25/05 17:00
                     Rest  30 minutes
   40.3  I90         ASHTABULA      S    I90 X229    OH     250.9 5:03 06/25/05 18:14
   21.1  S11         COLEBROOK      E    U322S11     OH     272.0 5:26 06/25/05 18:37

Total elapsed time:        5:26
Total trip mileage:         272.0      Impedance:       2125.6

Routing parameters used to calculate the route-

  Routing type: HRCQ Preferred Route with 2 driver(s)
    Preferred roads     Time bias: 1.00  Mile bias: 0.00, Toll bias: 1.00
    Nonpreferred roads  Time bias: 0.00  Mile bias: 1.00, Toll bias: 1.00, Penalty fac

  Constraints used on route:
    Prohibit use of links prohibiting truck use
    Prohibit use of ferry crossing
    Prohibit use of roads with Radioactive materials prohibition
```

Figure OX-13. TRAGIS standard listing output.

TRAGIS has preset biases incorporated into the routing portion of the code. These biases determine the time traveled between each of its nodes. TRAGIS also assumes two drivers per truck for each shipment and 30-minute rest periods at approximately every 250 miles. Because of the required rest periods and also for trips that take significantly less than 24 hours, the trip speed needed is the effective speed that reflects time when the truck isn't moving. At a constant 55 mph, a truck will travel 2,124 km in 24 hr. For the shortest trips considered (822 km for yellow cake shipments and 1,216 km between the closest regional sites), if an effective trip duration of 24 hr is assumed, then the effective speeds for these two trips are 21 mph = 34 km/hr = 822 km/24 hr and 31 mph = 51 km/hr = 1,216 km/24 hr, respectively. So, if the high and low values of the triangular speed distribution are taken to be 55 mph and either 21 or 31 mph, respectively, and the modal values is placed at about two thirds of the range, then the modal value will be about 47 mph = 75 km/hr = 1,800 km/24 hr.

As stated above, this analysis assumes that SNF, MOX, and vitrified HLW will be shipped by dedicated trains, which, when compared to regular freight trains, are likely to make fewer stops in yards and may travel at higher speeds. Nevertheless, although the values of sSpeed calculated using the preceding equation may underestimate dedicated train speeds, the speeds calculated with this equation were used to calculate trip costs without further adjustment.

OX-6. RAILWAY TARIFF (sTariff)

Feizollahi et al. (1995) contains data on railway transportation tariffs. These data are plotted in Figure OX-14. Values in this figure have been escalated to 2006 dollars and converted to metric units. Although the data in Figure OX-14 displays some scatter, it is well fit via regression by the following equation.

$$\text{sTariff}_{av} = 3.27\ \text{sTrip}^{-0.4221}. \tag{20}$$

The standard error of the estimate for this equation was 0.304 $/tonne-km. If one assumes a normal distribution of data about the regressed line, then sTariff becomes

$$\text{sTariff} = (\text{N}|\text{sTariff}_{av},.304) \tag{21}$$

which is the equation that was used to calculate sSpeed during the Monte Carlo calculation of Trip Costs.

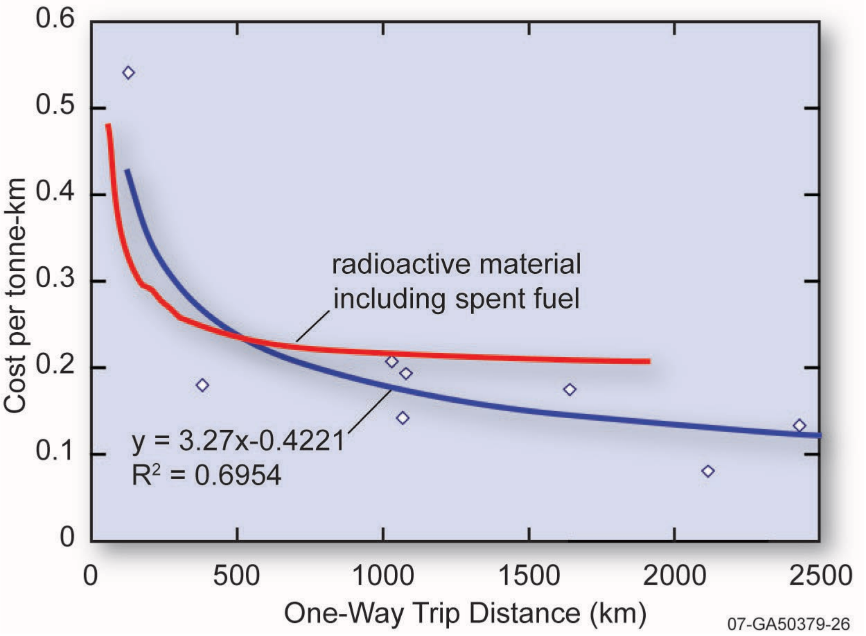


Figure OX-14. Railway tariff as a function of trip distance.

Except for the cost of single-use canisters (sCanCost), low, modal, and high values for triangular distributions were selected (1) by review of the costs associated with the shipment of damaged radioactive Three Mile Island (TMI) reactor components to INL (Fultz et al. 1987), (2) by discussions with staff of the Sandia National Laboratories Shipping and Receiving Department, and (3) based on operational experience of technical staff at Sandia or other government research laboratories.

Although a specific loading parameter and its analogous unloading parameter could have different triangular distributions (different low, modal, and high values), the calculations presented here assumed that they were the same.

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