# WASTE DISPOSAL ECONOMICS: A LIFE CYCLE COST MODEL

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## ABSTRACT

The nuclear waste disposal program, a major investment for the United States, should be carried out with a concern for cost-effectiveness. This paper describes a computer model designed to allow one to explore and compare the cost-effectivenss of different waste disposal options. The model, a relatively aggregated representation of the life cycle costs associated with moving, processing, and ultimately disposing of nuclear waste, consists of six submdules. The submodels represent the various functions which must be performed as spent fuel moves from the reactor to the repository. In this paper, the model is used to explore the cost-effectiveness of an illustrative parametric variation, the selection of the commercial high-level waste form diameter. Cost curves illustrate how specific and system-wide costs vary as the waste form diameter is varied.

## INTRODUCTION

Nuclear waste disposal constitutes a major investment for the United States. Estimates of the total costs involved in isolating nuclear waste from the biosphere are of the order of tens of billions in 1982 dollars. Any investment of this magnitude involves numerous engineering and policy issues which, if one is to avoid unnecessary expenditures of resources, should be resolved with a concern for cost-effectiveness.

This paper identifies some of those waste management issues. It then describes a computer model designed to allow one to explore and compare the cost effectiveness associated with different resolutions of the issues. Finally, the paper describes the model's application to a current waste package design issue, the selection of the commercial high-level waste (CHLW) form diameter.

## ENGINEERING ISSUES AND MODELING PHILOSOPHY

In defining the ultimate waste disposal system, one is faced with issues such as what is the optimum dimension for the waste form, should the volume of transuranic wastes (TRU) be reduced prior to disposal, is aging of waste a cost-effective policy, do changes in the thermal limits governing waste emplacement significantly affect costs, do changes in relative prices significantly affect the real costs of waste management, etc.

If one is concerned with cost-effectiveness, the resolution of these issues should involve the analysis of what are often complicated economic tradeoffs. One difficulty, however, is that efficient analyses require direction and guidance which generally only emanate from one who has already analyzed the issues' tradeoffs and consequently has a sense for their relative importance. However, decisionmakers and designers are not often afforded the luxury of being faced with issues they previously have resolved. As a result, a great deal of time may be spent pursuing a variety of arbitrary possible solutions.

The model described in this paper has been formulated to provide designers with a relatively quick and flexible way of exploring issues and their implicit economic tradeoffs. The insight gained by this sort of preliminary analysis can enhance one's ability to steer subsequent detailed analyses more efficently.

The model is a relatively simple, aggregate representation of the life cycle costs of the nuclear waste management system. Its design is the product of a number of factors. First, the waste management issues and parameters of concern can affect costs throughout the waste's life cycle. Hence, there is a need for simulating the waste management system from reactor to repository. Second, although the economic issues are relatively complex, the data, at this particular time, are not very precise. That is, because the waste management problem is still being defined, little design and cost data exist which are both precise and relevant. Consequently, a relatively aggregated model is suggested. Third, because the model is to provide a relatively quick overview of the issues and their tradeoffs, insight and understanding are best served by logic which is easily communicated and understood; thus a relatively simple model is adequate.

## THE MODEL

The computer code, the Waste Disposal Cost Model (WADCOM), simulates the costs of treating and handling nuclear waste throughout any one of various user selected scenarios. More specifically, the model consists of relatively aggregated submodules linked together in such a way that one can simulate the life cycle costs of various nuclear waste disposal scenarios.

The specific submodules included in WADCOM are:

- o a waste logistics submodule
- o a spent fuel and CHLW transportation submodule
- o an interim storage submodule
- o a vitrification submodule
- o a repository submodule
- o a financial submodule.

These submodels are described in turn.

### The Waste Logistics Submodule

The waste logistics submodule keeps an accounting of the quantities of spent fuel by age through time.

Spent fuel enters the simulated waste isolation system from either an existing inventory or as future projected discharges. One is able to specify a waste design age -- the minimum age of the waste at time of disposal -- and calculate the system costs associated with treating and handling the specified waste quantities as they move from the reactor to the repository.

## The Spent Fuel and Commercial High-Level Waste Transportation Submodel

The spent fuel (SF) and commercial high-level waste (CHLW) transportation submodule is called into operation whenever the waste isolation scenario requires waste to be transported from one geographic location to another. The transportation cask fleet size and capital costs, the costs of hauling the waste between locations, and the fleet's maintenance costs are calculated in this submodule. The transport cask designs and capacities are sensitive to the waste age, and in the case of CHLW, diameter of the waste form. Total transportation costs thus vary with age of the waste and diameter of the waste form in addition to the submodule's other parameters.

Specifically,

$$\text{Cask Fleet}(WT,t) = \frac{\text{Waste Trans}(WT,t)}{\text{Waste Trans/Cask-Year}(WT)} \quad (1)$$

$$\frac{\text{Waste Trans}}{\text{Cask-Year}}(WT) = \frac{\text{Trips}(WT)}{\text{cask-year}} * \text{Cask Cap}(WT) \quad (2)$$

where WT is waste type:
t is time.

Cask capacity is a function of waste age and waste form diameter for CHLW and waste age and assembly type for SF.

$$\text{Cask Cap}(WT) = f(\text{Waste Age, Waste Size}(WT)) \quad (3)$$

where waste age and waste size are exogenous.

Trips per cask-year depend upon the time it takes for a cask to make a round trip between the waste source and the waste destination and the days per year the cask can be used.

$$\frac{\text{Trips}}{\text{Cask-Year}}(WT) = \frac{(\text{days/year}) * \text{Utilization}}{\text{Turnaround time }(WT)} \quad (4)$$

where utilization is the percent of the year the cask is available for use and is exogenous.

Turnaround time depends upon the distance the waste is being transported, the speed that the cask moves, and the time required for loading and unloading.

$$\text{Turnaround time}(WT) = \left(2 * \text{Distance} * \frac{1}{\text{speed}}\right) + \text{Handling time}(WT) \quad (5)$$

where Distance is the one way distance between the waste origin and destination and is exogenous
speed is the speed at which the cask travels and is exogenous
Handling time is the time required to load and unload the cask.

Cask capital costs are the annual costs of purchasing new transport casks. In the first year of waste transportation these costs are the costs of the cask fleet for that year. In subsequent years, the costs are the costs of purchasing any additions to the original cask fleet. The additions to the cask fleet are

$$\text{Cask Delta}(WT,t) = \text{Cask Fleet}(WT,t) - \text{Cask Fleet}(WT,t-1) \quad (6)$$

If the cask delta variable is negative, there are no cask capital costs in year t since adequate capacity exists to transport the existing waste. If the variable is positive, cask capital costs are

$$\text{Cap Cost}(WT,t) = \text{Cask Delta}(WT,t) * \text{Unit Cost}(WT) \quad (7)$$

where unit cost is the cost per cask and is exogenous.

Two costs are involved in operating the cask fleet. The first is the hauling cost. The hauling cost is related to the distance traveled and the weights of the loaded and unloaded casks. The per ton costs of hauling the loaded and unloaded casks are

$$\frac{\text{Cost-Empty}}{\text{ton}} = \alpha_1 * \ln(\text{Distance}) + \beta_1 * \text{Distance} \quad (8)$$

$$\frac{\text{Cost-Loaded}}{\text{ton}} = \alpha_2 * \ln(\text{Distance}) + \beta_2 * \text{Distance} \quad (9)$$

where $\frac{\text{Cost-empty}}{\text{ton}}$ is the cost per ton to transport the empty cask the one way distance
$\frac{\text{Cask-loaded}}{\text{ton}}$ is the cost per ton to transport the loaded cask the one-way distance.
$\ln$ is the natural log
$\alpha$'s and $\beta$'s are estimated parameters.

The total hauling cost in year t is then

$$\text{Hauling Cost}(WT,t) = \left[\left(\frac{\text{Cost-Empty}}{\text{ton}} * \text{Weight Empty}\right) + \left(\frac{\text{Cost-loaded}}{\text{ton}} * \text{Weight loaded}\right)\right] * \text{Cask Fleet}(WT,t) * \frac{\text{Trips}}{\text{Cask-year}}(WT) \quad (10)$$

The second operating cost is a maintenance cost which varies with the fleet size.

$$\text{Maintenance Cost}(WT,t) = (\text{Maintenance Cost/Cask}) * \text{Cask Fleet}(WT,t)$$

where $\frac{\text{Maintenance Cost}}{\text{Cask}}$ is exogenous (11)

Total operating costs are the sum of hauling and maintenance costs.

$$\text{Operating Costs}(WT,t) = \text{Hauling cost}(WT,t) + \text{Maintenance Cost}(WT,t) \quad (12)$$

## The Interim Storage Submodule

The interim storage submodule is called into operation if one chooses to delay ultimate waste disposal, in order to age the waste, for example. The submodule consists of various equations describing the interim storage facility's capital costs, its operating costs, its surveillance costs, the cost of retrieving the waste, and the cost of decommissioning the facility.

The interim storage facility's capital cost consists of a fixed plus a variable cost.

$$\text{Int Store Cap Cost}(t) = \text{FCC} + \text{VCC} * \left[\frac{\text{Max MTU}}{\text{Design MTU}}\right]^{\beta_1} * \text{ISDIST}(t) \quad (13)$$

where FCC is the fixed capital cost for a reference design
VCC is the variable capital cost for a reference design
Max MTU is the maximum annual rate at which waste is received
Design MTU is the annual rate for which the reference facility was designed to receive waste
$\beta 1$ is a scaling parameter
ISDIST(t) is the proportion of total capital costs incurred in year t.

Operation of the interim storage facility includes a filling operation, a caretaker operation, and a retrieval operation. The filling operation is

$$\text{Filling Cost}(t) = \text{FFC} + \text{VFC} * \left[\frac{\text{MTU }(t)}{\text{Design MTU}}\right]^{\beta 2} + (\text{Well Cost} + \text{Canister Cost}) * \frac{\text{MTU}(t)}{\text{MTU/Can}} \quad (14)$$

where FFC is the fixed filling cost
VFC is the variable filling cost
MTU(t) is the actual rate at which waste is processed during year t
$\beta_2$ is a scaling parameter
well cost is the cost of constructing one dry well storage unit
canister cost is the cost of the canister emplaced in the dry well storage unit
$\frac{\text{MTU}}{\text{Can}}$ is the amount of waste per canister

Caretaker operations are assumed to be

$$\text{Caretaker Cost}(t) = \text{CVC} * \left[\frac{\text{INV}(t)}{\text{Design INV}}\right]^{\beta_3} \quad (15)$$

$$\text{INV}(t) = \sum_t \text{MTU}(t) \quad (16)$$

where CVC is the variable caretaker cost associated with the reference design
INV(t) is the inventory of waste in the storage facility at time t
Design INV is the inventory of waste for which the facility was designed
$\beta_3$ is a scaling parameter.

Retrieval costs consist of a fixed and variable costs.

$$\text{Retrieval Cost}(t) = \text{RFC} + \text{RVC} * \left[\frac{\text{MTU Ret}(t)}{\text{Design Ret}}\right]^{\beta_4} \quad (17)$$

where RFC is the fixed retrieval cost
RVC is the variable retrieval cost
MTU Ret(t) is the amount of waste retried during year t
Design Ret is the rate for which the facility was designed to retrieve waste
$\beta_4$ is a scaling parameter.

Finally, decommissioning costs are a fixed proportion of total interim storage capital costs.

$$\text{Decom Cost}(t) = \text{DECOM} * \text{Int Store Cap Costs} * \text{ISDEDIST}(t) \quad (18)$$

where DECOM is the ratio of decommissioning costs to total capital costs
ISDEDIST(t) is the proportion of decommissioning costs incurred in year t

## The Vitrification Submodule

The logic of the vitrification submodule is based upon the logic of a more detailed reprocessing model, WMEM.(1) The vitrification submodule is called when one chooses a scenario involving reprocessing. The submodule consists of equations describing the capital, operating, and decommissioning costs for four vitrification costs centers; liquid waste storage, liquid waste solidification, hulls treatment, and general process trash treatment. The major parameters affecting the vitrification costs are the annual throughput (in MTU) and the size of the high-level waste canister.

The vitrification complex is assumed to be of fixed capacity (1,500 MTU/yr) and treated in the submodule as a single capital cost distributed over an exogenous construction period.

$$\text{Vit Capital Cost}(t) = \text{Capital Cost} * \text{VDIST}(t) * \text{VMULT}(\text{Throughput}) \quad (19)$$

where Capital cost is the cost of one fixed capacity vitrification complex and is exogenous
VDIST(t) is the proportion of total capital costs incurred in year t and is exogenous
VMULT (throughout) is a multiplier which increases the capital cost as a function of MTU throughput.

Operating costs in the submodule are fixed for all but the liquid waste solidification function. The fixed portion of these costs, which increases as one exceeds the throughput capacity of the 1,500 MTU/Year facility, is

$$\text{Vit Op Cost}(t) = \text{Fixed Cost} * \text{VMULT}(\text{throughput}) \quad (20)$$

Liquid waste solidification costs, on the other hand, consist of a canister cost, and a glass frit cost, both of which are variable.

$$\text{Canister Cost}(t) = \text{Cost/Can} * \text{Cans}(t) \quad (21)$$

$$\text{Can Cost} = f^2 \text{ (Can Diameter)} \quad (22)$$

$$\text{Glass Cost}(t) = \text{Unit glass cost} * \text{glass}(t) \quad (23)$$

where glass(t) is the total glass used in year t.

The amount of glass used during year t is calculated as follows.

$$\text{Glass}(t) = \frac{\text{Glass}}{\text{Can}} * \text{Cans}(t) \quad (24)$$

The weight of glass per canister is found as a product of the canister volume, the percentage of the canister filled with waste glass product, the density of the waste glass product, and the percentage of the waste glass product weight which is glass frit.

$$\frac{\text{Glass}}{\text{Can}} = \text{Can Volume} * \text{Fill} * \text{Waste Glass Density} * (1\text{-WLOAD}) \quad (25)$$

$$\text{Can Volume} = \text{f3 (Can Diameter)} \quad (26)$$

$$\text{Waste Glass Density} = 1/\left[\frac{\text{WLOAD}}{\text{OXDENSI}} + \frac{1\text{-WLOAD}}{\text{GLASSDENSI}}\right] \quad (27)$$

where fill is the percentage of the canister volume filled with waste glass product and is exogenous
WLOAD is the weight-to-weight ratio of waste oxides to total waste glass product and is exogenous
OXDENSI is the density (weight/volume) of the waste oxides and is exogenous
GLASSDENSI is the density (weight/volume) of the glass frit and is exogeneous.

The number of canisters used during any year t is found by first calculating the equivalent MTU per CHLW canister and dividing that value into the annual vitrification processing rate.

$$\frac{\text{MTU}}{\text{Can}} = \frac{(\text{Glass/Can}) * (\text{WLOAD/1-WLOAD})}{\text{Waste Oxides/MTU}} \tag{28}$$

$$\text{Can}(t) = \frac{\text{Vit Processing Rate}(t)}{\text{MTU/Can}} \tag{29}$$

where waste oxides/MTU is the weight of waste oxides resulting from each MTU reprocessed and is exogenous.

Total operating costs for any year t are

$$\text{Total Op Cost}(t) = \text{Vit Op Cost}(t) + \text{Can Cost}(t) + \text{Glass Cost}(t) \tag{30}$$

Decommissioning costs are assumed to be a fixed percentage of total capital costs and distributed over an assumed decommissioning schedule.

$$\text{Decom Cost}(t) = \text{Tot Cap cost} * \text{DECOM} * \text{VDEDIST}(t) \tag{31}$$

where DECOM is the ratio of decommissioning costs to total capital costs and is exogenous
VDEDIST(t) is the percentage of decommissioning costs incurred in year t and is exogenous.

## The Repository Submodule

The repository submodule consists of equations describing the capital, operating, and decommissioning costs of a number of repository subsystems. The logic in this repository submodule is separated into two groupings: waste preparation costs and repository costs.

Waste preparation costs consist of the capital, operating, and decommissioning costs of the waste packaging facility and the costs of the waste packages. The packaging facility capital costs consist of fixed and variable costs. The capital costs for any year t are

$$\begin{aligned} \text{Package Fac Cap Cost }(\text{WT},t) = {} & [\text{WPFC}(\text{WT}) \\ & + \text{WPVC}_1 * (\text{Max MTU/Design MTU})^{\beta_1} \\ & + \text{WPVC}_2 * (\text{Max Packages/Design Packages})^{\beta_2}] \\ & * \text{PDIST}(t) \end{aligned} \tag{32}$$

where WPFC(WT) is the waste package facility fixed capital cost
WT is waste type
WPVC1,2 are the variable capital costs
Max MTU is the maximum MTU processed through the packaging facility in any year t
Design MTU is the rate at which the reference packaging facility is designed to process waste
Max Packages is the maximum number of waste packages processed through the packaging facility during any year
Design Packages is the annual rate for which the reference packaging facility is designed to package waste
PDIST(t) is the percentage of total packaging facility capital costs incurred during year t
$\beta$'s are scaling parameters.

Waste preparation operation costs consist of the packaging facility's operation costs and the costs of the waste packages.

$$\begin{aligned} \text{Package Fac Op Cost}(t) = {} & \text{WPFOC} + \\ & \text{WPVOC1} * \left[\frac{\text{MTU}(t)}{\text{Design MTU}}\right]^{\beta_1} + \\ & \text{WPVOC2} * \left[\frac{\text{Packages}(t)}{\text{Design Packages}}\right]^{\beta_2} \end{aligned} \tag{33}$$

where WPFOC is the waste packaging facility fixed operating cost
WPVOC1,2 are the waste packaging facility variable operating costs
MTU(t) is the actual MTU processed through the packaging facility in year t
Packages(t) is the actual number of waste packages processed through the facility in year t
$\beta$'s are weighting parameters.

Waste package material costs are the costs of the carbon steel and titanium overpacks used to encase the waste. These material costs are estimated for any given sized waste package by scaling the costs of an existing waste package design as follows:

$$\text{Package Mat Costs}(\text{WT},t) = \text{MPROP}(\text{WT}) * \text{REFCOST}(\text{WT}) * \text{Packages }(\text{WT},t) \tag{34}$$

$$\text{MPROP}(\text{WT}) = \frac{[\text{ID}(\text{WT}) + \text{THICK}(\text{WT})]^2 - \beta(\text{WT}) * \text{ID}(\text{WT})^2}{\text{VOLSURROGATE }(\text{WT})} \tag{35}$$

where REFCOST(WT) is the cost of a reference waste package for waste type WT
Packages(WT,t) is the number of packages of waste type WT processed during year t
MPROP(WT) is a scaling factor
ID(WT) is the inside diameter of the waste package used for waste type WT
THICK(WT) is the total wall thickness of the waste package used for waste type WT
VOLSURROGATE(WT) is a surrogate for the volume of material in the reference waste package
$\beta$(WT) is a parameter which scales for the material in the waste packages top and bottom lids

Total operating costs for any year t are

$$\text{Waste Prep Op Costs}(t) = \text{Package Fac Op Costs}(t) + \sum_{\text{WT}} \text{Package Mat Costs}(\text{WT},t) \tag{36}$$

Packaging facility decommissioning costs are simply a percentage of the facility's capital costs.

$$\text{Decom Costs}(t) = \text{Package Fac Tot Cap Cost} * \text{DECOM} * \text{WPDIST}(t) \tag{37}$$

where DECOM is the ratio of total decommissioning costs to total waste packaging facility capital costs

WPDIST(t) is the percentage of waste packaging facility decommissioning costs incurred in year t

As with waste preparation costs, repository costs are separated into capital, operating, and decommissioning categories. As in the previous submodules, repository capital costs consist of both fixed and variable components. The fixed components are assumed constant over a wide range of waste throughput and capacity and are distributed over an assumed construction period.

$$\text{Fixed Cap Costs}(t) = \text{Fixed Cap Cost}* \text{RDIST}(t) \qquad (38)$$

where RDIST(t) is the fraction of total construction costs incurred in year t.

Variable capital costs are relatively sensitive to waste throughput and capacity. They consist of the costs of constructing the receiving facility, the costs of mining a certain fraction of total waste emplacement rooms and corridors and the costs of a fraction of the total waste emplacement equipment.

The receiving facility costs are

$$\text{Rec Fac Cap Cost}(t) = \text{RVC} * (\text{Max MTU}/\text{Design MTU})^{\beta} * \text{RDIST}(t) \qquad (39)$$

where RVC is the cost of the reference design receiving facility and is exogenous
$\beta$ is a scaling parameter
Max MTU is the maximum rate at which waste is processed per year
Design MTU is the annual rate for which the reference receiving facility is designed to receive waste.

The cost of emplacement rooms accruing to the capital account is an arbitrary proportion of total room costs and is found as follows.

$$\text{Room Cost}(t) = \text{FROOM} * \text{TRMAS} * \text{UMC} * \text{RDIST}(t) \qquad (40)$$

$$\text{TRMAS} = \sum_{t}\sum_{WT} \text{ARMAS}(WT,t) \qquad (41)$$

$$\text{ARMAS}(WT,t) = \text{AREA}(WT) * \text{ROOMH}(WT) * \text{DENSI} * \text{Packages}(WT,t) \qquad (42)$$

$$\text{AREA}(WT) = \text{ROOMW}(WT) * \text{Pitch}(WT) \qquad (43)$$

where FROOM is the fraction of total room costs allocated to capital
UMC is a unit mining costs
ROOMH(WT) is the room height for waste type WT
DENSI is the density (weight/volume) of the geologic medium
ROOMW(WT) is the room width for waste type WT
Pitch(WT) is the distance from waste package centerline to centerline.

The pitch variable and the equations from which it is calculated approximate the heat transfer characteristics of the waste in the repository. For high-level waste, the pitch equations relate waste form diameter for a given aged waste -- a value implying some initial heat content --to waste package pitch. The parameters of this equation change with waste age so that for a given size waste package, pitch changes as the waste age changes. The equation allows one to trade off, for a given aged waste, the decreased costs of larger but fewer waste packages against the increased costs of mining. As a result, one is able to optimize the waste package diameter by searching for the pitch and diameter which result in the lowest total costs.

Pitch is assumed constant for RHTRU and CHTRU; it is assumed that these waste types generate no heat. For high-level waste, either SF or CHLW, pitch is the maximum of three values: the pitch necessary to preclude the waste form centerline temperature from exceeding its limit; the pitch necessary to preclude the temperature of the geologic medium from exceeding its limit; and the pitch necessary to preclude the repository from exceeding its total energy limit. The specific equations used to approximate the centerline, geology, and far-field limiting pitches are:

$$\text{PitchC}(WT,A) = \text{EXP}\,[\alpha_C(WT,A) + \beta_C(WT,A) * \text{ID}(WT)] \qquad (44)$$

$$\text{PitchG}(WT,A) = \text{EXP}\,[\alpha_G(WT,A) + \beta_G(WT,A) * \text{ID}(WT)] \qquad (45)$$

$$\text{PitchF}(WT,A) = \alpha_F(WT,A) + \beta_F(WT,A) * \text{ID}(WT) \qquad (46)$$

where EXP is the exponential
$\alpha$'s and $\beta$'s are estimated parameters
ID(WT) is the inside diameter of the waste package containing waste type WT
A is waste age.

The most limiting pitch, the maximum of the three valves calculated in eqs. (44) through (46), is the one used to calculate actual mining costs.

$$\text{Pitch}(WT) = \text{Max}\,[\text{PitchC}, \text{PitchG}, \text{PitchF}] \qquad (47)$$

Transfer equipment costs allocated to capital are an arbitrary fraction of total equipment costs.

$$\text{Trans Eq Cost}(t) = \text{FTREQ} * \text{TTREC} * \text{UTC} * \text{RDIST}(t) \qquad (48)$$

$$\text{TTREC} = \sum_{t} \text{ATREC}(t) \qquad (49)$$

$$\text{ATREC}(t) = \text{Packages}(t)/\text{NEMPL} \qquad (50)$$

where FTREQ is the fraction of transfer equipment costs allocated to capital
UTC is the unit cost of transfer equipment
ATREC(t) is the transfer equipment required during year t
Packages(t) is total waste packages emplaced during year t
NEMPL is the emplacement lifetime of each transporter in packages per lifetime.

The corridor costs allocated to capital are simply proportional to the room costs allocated to capital.

$$\text{Corridor Cost}(t) = \beta * \text{Room Cost}(t) \qquad (51)$$

where $\beta$ is a parameter representing the amount of corridors mined per room.

Repository operating costs consist of both fixed and variable components. The fixed components represent the costs of operating certain facilities whose operation is assumed insensitive to waste throughput or repository capacity. They are

$$\text{Fixed Op Costs}(t) = K \qquad (52)$$

The variable costs represent costs which are sensitive to waste throughput, waste package diameter, or repository capacity. These variables costs are

$$\text{Rec Fac Op Cost}(t) = \text{RFOC} * (\text{MTU}(t)/\text{Design MTU}) \quad (53)$$

$$\text{Room Cost}(t) = \sum_t (\text{ARMAS}(\text{WT},t)) * [(1-\text{FROOM}) * (\text{UMC} + \text{BKC}) + \text{FROOM} * \text{BKC}] \quad (54)$$

$$\text{Borehole Costs}(t) = \text{Packages}(\text{WT},t) * \text{BHC}(\text{WT}) \quad (55)$$

$$\text{BHC}(\text{WT}) = \text{D}(\text{WT}) * [\beta_1 * (\text{ID}(\text{WT}) + \text{THICK}(\text{WT}))^{\beta 2}] \quad (56)$$

$$\text{Empl Cost}(t) = [(1-\text{FTREQ}) * \text{ATREC}(t) * \text{UTC}] + [\text{Packages}(\text{WT},t) * \text{EMPLC}] \quad (57)$$

$$\text{Corridor Cost}(t) = \beta * \text{Room Cost}(t) \quad (58)$$

where RFOC is the annual variable cost of operating the reference receiving facility
MTU(t) is the actual MTU's processed through the receiving facility in year t
BKC is the unit room backfilling cost
Packages(WT,t) are the number of packages of waste type WT processed in year t
D(WT) is the depth of the borehole for waste type WT
$\beta 1$, $\beta 2$ are estimated parameters
ID(WT) is the inside diameter of the waste package containing waste type WT
THICK(WT) is the total wall thickness of the waste package containing waste type WT
EMPLC is a labor cost of emplacing one waste package
$\beta$ is a parameter representing the amount of corridors mined per room.

Decommissioning costs are assumed to be a fixed percentage of total capital costs plus the costs of rooms and corridors mined during repository operations.

$$\text{Decom Costs}(t) = \text{DECOM} * [\text{Total Cap Cost} + \text{Room Cost} + \text{Corridor Cost}] * \text{RDDIST}(t) \quad (59)$$

where RDDIST(t) is the proportion of total decommissioning costs incurred in year t

## The Financial Submodule

The financial submodule consists of equations which allow one to perform two operations. First, the submodule allows one to incorporate real price trends into each of the previously described submodules. That is, the submodule allows the user to either keep relative prices constant over time or to let them change so that real, constant dollar costs change with time. Second, the submodule allows one to discount the time streams of constant dollar costs to their present value with a user supplied discount rate.

Capital, operating, and decommissioning costs are adjusted for relative price trends as follows.

$$\text{Real Cap Cost}(i,t) = \text{Cap Cost}(i,t) * \left[\frac{1+r_c(i)}{1+g}\right]^I \quad (60)$$

$$\text{Real Op Cost}(i,t) = \text{Op Cost}(i,t) * \left[\frac{1+r_o(i)}{1+g}\right]^I \quad (61)$$

$$\text{Real Decom Cost}(i,t) = \text{Decom Cost}(i,t) * \left[\frac{1+r_d(i)}{1+g}\right]^I \quad (62)$$

where $r_c(i)$ is the annual rate at which capital costs of type i change
$r_o(i)$ is the annual rate at which operating costs of type i change
$r_d(i)$ is the annual rate at which decommissioning costs of type i change
g is the annual rate at which the GNP deflator changes
I is the number of years between the base year and the simulated year t

Once the costs have been adjusted for relative price trends, they are discounted to their present value as follows

$$\text{PV Cap Costs}(i) = \sum_t \frac{\text{Real Capital Cost}(i,t)}{(1+\text{DSCNT})^I} \quad (63)$$

$$\text{PV Op Costs}(i) = \sum_t \frac{\text{Real Op Costs }(i,t)}{(1+\text{DSCNT})^I} \quad (64)$$

$$\text{PV Decom Costs}(i) = \sum_t \frac{\text{Real Decom Costs }(i,t)}{(1+\text{DSCNT})^I} \quad (65)$$

where DSCNT is the real discount rate
i refers to submodule i
I is the number of years between the base year and the simulated year.

## MODEL APPLICATION

As mentioned previously, the model has been used to analyze a current design issue. That issue involves selecting the CHLW form diameter. The selection of the CHLW form diameter involves a number of interesting economic and non-economic tradeoffs. Only explicit economic tradeoffs and those non-economic tradeoffs having an obvious economic effect are considered in this illustrative exercise of WADCOM however.

The example simulated by the model consists of 72,000 MTU of spent fuel being received at reprocessing plants beginning in 1998 and within one year of reprocessing being vitrified and shipped to a salt repository for overpacking and disposal. The age of the waste at time of emplacement is assumed to be at least ten years.

The selection of the CHLW form diameter affects the costs of vitrification, transportation, and disposal. Vitrification costs are affected primarily by the number and size of the stainless steel canister into which the glass waste is poured. For a fixed length, the number of canisters is inversly proportional to the square of the waste form diameter; since the total volume of waste is fixed, the larger the volume of waste in any one waste form, the fewer waste forms there are. The cost of the canister is directly proportional to the diameter of the waste form; as the waste form's diameter gets larger,the cost of the canister increases. The economic tradeoff in the vitrification process is thus the increased cost per canister resulting from a larger waste form size versus the decreased number of canisters.

Transportation costs are affected by waste form size in a number of ways. As the waste form gets larger, the capacity of the transportation cask decreases because of its relatively fixed capacity. As a result, the size of the cask fleet and the number of trips necessary to transport the waste increase. Cask capital and operating costs increase accordingly. The capacity of the transportation cask does not change monotonically with the size of the waste form, however; it remains constant until one of the cask constrains is exceeded and then changes by some given increment. Total transportation costs follow this same pattern.

The repository costs are affected by the waste form diameter for two basic reasons. First, handling and waste packge material costs change as the size and number of waste packages change. Second, mining costs change as the waste package spacing changes. The first cost effect is fairly obvious. As the waste form becomes larger, for example, and contains more waste, fewer waste packages are needed to dispose of the same volume of waste. Handling and waste package material costs decrease because of the fewer numbers. Furthermore, fewer boreholes are required reducing mining costs correspondingly.

The second cost effect is related to the repository and waste package heat transfer characteristics. This effect is more complicated. As mentioned previously, three thermal limits affect the way in which waste can be emplaced in the repository. The centerline temperature limit cannot be exceeded without devitrifying the waste form, a condition possibly leading to unacceptable radionuclide migration. The near field temperature limit cannot be exceeded without causing the salt in the repository to decrepitate, a condition leading to possible waste package failure. The far field limit, a limit governing the total energy entering the repository, cannot be exceeded without causing unacceptable uplift to the repository site and other effects.

The actual temperatures occuring in the repository and waste glass and the actual energy transferred to the repository geology depend on the initial amount of heat in a waste package, the number of packages in the repository, and the spacing of the packages relative to one another. For a fixed length waste form of a fixed waste loading and age one can avoid violating the temperature and energy limits when changing the waste form diameter by changing package spacing. Each combination of waste form size and package spacing has associated with it a repository cost as well as a vitrification and transporation cost. It is not immediately obvious, however, what the costs are or in what direction they move as one moves along the waste form size - package spacing curve.

Using WADCOM it is possible to similate the repository and system costs associated with waste forms of different diameters. Figure 1 illustrates the way in which costs from the different submodules are affected as the waste form diameter changes. The figure includes repository costs, vitrification costs, transportation costs, and total system costs are functions of the waste form diameter.

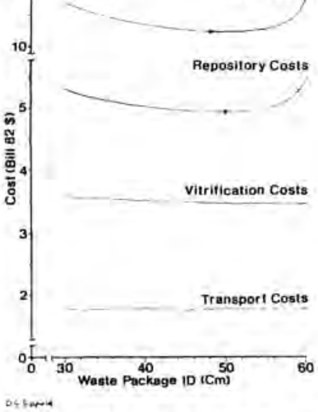

Fig. 1. Costs for CHLW Aged 10 Years.

Two points regarding Figure 1 are noteworthy. First, the repository costs follow a "U" shaped path as the waste form diameter changes, i.e, a waste form diameter exists for which repository costs are less than any other diameter. The "U" shape makes sense intuitively when one considers that at the extremes of the cost curve one has either an extremely large number of waste packages or an extremely large distance between any two waste packages. Each of these extremes leads to extremely large costs.

Second, the minimum cost diameters on the repository cost curve and the total cost curve differ. What is optimum from the repository perspective is not optimum from the total system perspective. This difference between the minimum points on the two curves is the result of vitrification and transportation costs. It is thus apparent that the choice of waste form size should include consideration of total system costs. Merely optimizing with respect to repository costs may lead to a less than optimum solution as far as total costs to society are concerned.

In summary, WADCOM is a relatively aggregated model which allows one to explore complicated economic tradeoffs quickly. In the example given, it is shown that changes in the size of the waste form affect waste disposal costs. Furthermore, the effect is system wide. The summation of these system wide effects results in a "U" shaped total cost curve which suggests that some waste form size exists which is less costly than any other. Using WADCOM in a systematic way, one could explore other design issues and began to rank them in terms of their economic importance. This sort of economic insight could then aid designers by helping them to allocate their effort more efficiently.

## REFERENCES

1. Godfrey, W. L., and R. J. Cholister, "Storage and Handling of Wastes form Uranium Fuel Processing Alternatives - Appendix G - A Nuclear Waste Management Economic Model", AGNS-1040-3.3-34, Appendix G, October 1978.