QUEUEING IN A SPENT FUEL TRANSPORTATION SYSTEM -

A PRELIMINARY ANALYSIS OF IMPLICATIONS FOR SYSTEM DESIGN

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ABSTRACT

Compliance with the Nuclear Waste Policy Act of 1982 (PL 97-425) will require the transportation of large volumes of spent fuel to a central receiving facility (Either a geologic repository or a monitored retrievable storage facility). Decisions on the transport mode and technology will evolve over the next several years, in anticipation of the deployment of a receiving facility in the late 1990s.

Regardless of the particular transportation mode or modes and the details of cask technology, the transport system from many diverse sources to a single point will generate an essentially random arrival pattern. This random arrival pattern will lead to the formation of queues at the receiving facility. As is normal in any queueing system, the waiting time distribution caused by this queueing will depend on the receiving facility input processing rate and the characteristics of the traffic. Since this is a cyclic system, there is also a reverse effect in which (for a given size cask fleet) average wait time affects traffic intensity. Both effects must be accounted for to properly represent the system.

This paper develops a simple analytic queueing model which accounts for both of these effects simultaneously. Since both effects are determined by receiving facility input rates and cask fleet size and characteristics, two major sets of system design parameters are linked by the queueing process. The model is used with estimated traffic and service parameters to predict the severity of queueing under plausible reference system conditions, and to establish "shadow prices" for the trade off between larger cask fleets and more efficient receiving facilities. Since many of the parameter values used in this estimation are quite preliminary, these results are presented primarily in the context of demonstrating the utility of the queueing model for future trade off studies.

INTRODUCTION AND SCOPE

A system in which spent nuclear fuel is shipped from many reactor pools to a few MRS or repository sites will tend to develop queues at the destinations. This queueing will effect the productivity of the cask fleet (and thus its optimal size) and that of the receiving facilities as well. While these effects have been widely recognized for some time, most cost and logistics models of the cask fleet (Ref. 1, 2) and receiving facility designs studies to date have not explicitly accounted for these effects.

This paper develops a very simple model of queueing in a spent fuel transport system, which is exploited to meet several objectives;

1. Determination of the probable impact of queues on cask fleet productivity (vis-a-vis current naive estimates).
2. Providing a framework in which the cask fleet size/receiving facility receipt rate decisions can be made simultaneously.
3. Estimation of preliminary shadow prices for receiving facility receipt rate capacity using current estimates of cask fleet productivity and costs.

In addition to these limited analytic objectives, this preliminary application of a simple queuing model to the spent fuel transport problem also serves to identify some fruitful areas for further research and to identify a useful framework for supporting cask fleet and receiving facility decisions by OCRWM.

THE REFERENCE SYSTEM

While many configurations of a spent fuel disposal system have been studied, all share the basic structure shown in Fig. 1. This is a simplified system characterization, but illustrates that spent

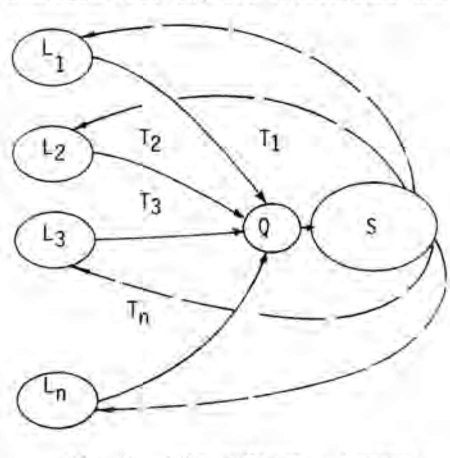

Fig. 1. The reference system.

fuel from many sources (reactors) contribute to the input stream for a single receiving facility.

This characterization is valid for any transport mode and for multiple receiving facility systems. For purposes of formulating the queueing model, the key characteristics of this system are:

1. Each of the at-reactor loading processes (L1...LN) is subject to random forces. Examples would include difficulties in handling certain assemblies, interference by external factors (other pool operations, etc.). Thus even for a given reactor, cask loading time is a random variable.

2. The transport processes (T1...TN) are similarly subject to random factors and transport time over any path is thus a random variable.

3. The variation among and between the loading and transport processes is statistically independent.

These characteristics are sufficient to guarantee that the arrivals at the receiving facility are randomly scheduled, and thus that interarrival time at the receiving facility is a random variable. While conditions 1-3 do not guarantee the form of the interarrival time distribution, they strongly suggest a "completely random" arrival stream - i.e., one in which arrival times are uniformly distributed and interarrival times follow the negative exponential distribution.

The service process S would consist of inspecting, washing, and unloading transport casks and readying them for discharge on another trip. While it cannot be shown empirically at this time, this service process seems to conform to Poisson process assumptions and is thus assumed to generate exponentially distributed service times.

Any receiving facility will provide for both truck and rail input. While both traffic streams could be modeled independently, our analysis assumes a single mode input (rail) to illustrate the effects of queueing. Current information on service times would not allow any great improvement on this method even if each traffic stream was modeled separately.

The number of channels in the service process S depends on the design of the receiving facility. For the current purposes, only the system service rate is important, and a single channel model is sufficient.

In addition to the input queue at the receiving facility, queues could develop at each of the reactors as casks waited for fuel loading. The extent to which this occurs will be strongly dependent on the system operating policy, however. If only a few campaigns (involving several casks per reactor) are conducted at once, this at-reactor queueing could make a large contribution to total system waiting time. Since alternative opportunities for cask utilization will always exist at other sites, it seems reasonable that an efficient cask dispatching system could minimize this at-reactor queueing. Since the emphasis here is on the effects of queueing on total system efficiency and cask fleet size, the possibility of at-reactor queueing is ignored in the analysis. More precisely, it is assumed that the waiting time contributed by at-reactor queues is a small fraction of that incurred at the receiving facility input.

Combined with our previous assumptions, this leaves a <u>very</u> simple model of the system - the M/M/1, a <u>single</u> channel model with exponentially distributed interarrival and service times. Clearly, using this model involves many simplifying assumptions, which remain to be validated or altered. Given the exploratory nature of this paper, this model provides an adequate analytical framework.

WAITING TIME IN THE M/M/1 MODEL

The M/M/1 model is one of the simplest of a class of analytic queueing models in which results for steady-state behavior are well known. The principal measures of this behavior are probability distributions for the length of the queue and the average time spent in the queue. For our purposes, the means of these distributions are sufficient to characterize the queueing process. As shown below, these measures of average performance are fairly simple measures of the assumed probability distributions for service and interarrival times.

The exponential probability distributions characterizing the arrival and service processes are single parameter distributions, given by;

$$PR\left\{T_A > t\right\} = e^{-\lambda t} \qquad [1a]$$

$$PR\left\{T_S > t\right\} = e^{-\mu t} \qquad [1b]$$

where

T_A = time between arrivals (a random variable).
T_S = service time (random variable).
λ = mean arrival rate (casks/unit time).
μ = mean service rate (casks/unit time).
t = time in an interval $(o, \Delta t)$.

A basic result for the M/M/1 queue (Ref. 3) is that expected waiting time is given by;

$$W_Q = \frac{\lambda}{\mu\ (\mu - \lambda)} \qquad [2]$$

W_Q = mean waiting time.
λ, μ = as in equations 1a and 1b, $\mu > \lambda$

Equation [2] provides the fundamental link between productivity of the cask fleet (as measured by λ and productivity of the receiving facility (as measured by μ). Note that μ must be strictly greater than λ to prevent buildup of infinite queues. Given the closed cycle nature of the system shown in Fig. 1, the receipt rate parameter λ is, other things equal, a function of the cask fleet size. Specifically,

$$\lambda = \left(\frac{AN}{Tc}\right) \qquad [3]$$

λ = arrival rate, casks/day.
A = annual cask availability, (fraction of year).
N = size of cask fleet.
Tc = average cycle time for a cask.

Formulations analogous to [3] have been used (given that λ was "known") in determining cask fleet size in several models of the spent fuel transport process (Ref. 1, and 2). In all cases, however, the cycle time Tc was taken to be exogenously determined. In fact, the cycle time Tc is the sum of travel, service, and waiting times in the system. Thus we can write;

$$\lambda = \frac{AN}{T_T + W_Q} \qquad [4]$$

where
λ, A, N as in Equation [3].
T_T = travel and service times.
W_Q = average queueing time.

This expresses λ as a function of W_Q, where [2] has W_Q as a function of λ. Solving both simultaneously (by substituting [4] in [2]) gives;

$$W_Q = \frac{\left(\frac{AN}{T_T + W_Q}\right)}{\mu\left(\mu - \left(\frac{AN}{T_T + W_Q}\right)\right)} \qquad [5]$$

This gives average system waiting time as a function of cask fleet size, availability, service rate, and travel time. After manipulation, [5] gives;

$$\mu^2 W_Q{}^2 + (\mu^2 T_T - \mu AN)\, W_Q - AN = 0 \qquad [6]$$

and

$$W_Q = \frac{\mu AN - \mu^2 T_T \pm \sqrt{\left(\mu^2 T_T - \mu AN\right)^2 + 4\mu^2 AN}}{2\mu^2} \qquad [7]$$

While it may be possible to simplify [7], it gives a reasonably compact closed form for average waiting time which accounts for both the effect of traffic intensity on waiting time and the effect of waiting time on traffic intensity. The next section explores the application of Eq. 7 to some typical reference system data and the implications for cask fleet sizing and receiving facility design decisions.

PARAMETER ESTIMATION

Before [7] can be put to use, some estimates of μ, T_T, and A must be made. This section develops some plausible numbers based on recent OCRWM documents.

The receiving facility service rate μ is determined by the design throughput rate of the facility. This figure is currently 3000 MTU/year for repositories and 3600 MTU/year for the MRS facility. The 3000 MTU figure is used in this analysis, simply because capacity factor estimates for the receiving hot cell were available for the repository (Ref. 4). Clearly, this 3000 MTU/year cannot be interpreted as the maximum instantaneous receipt rate, since to do so would make $\lambda = \mu$ and the input queue unstable. This leads to the question of how the 3000 MTU/year should be interpreted in a queueing context. The best guidance on this point comes from Ref. 4 which indicates planned operation of the repository receiving facility for 250 days per year. This gives an input capacity factor of about 68.5%, or an instantaneous receiving facility capacity of 4380 MTU/year. For purposes of application of Eq. [7], this MTU figure was converted to casks per day assuming TTC reference rail cask capacities of 12 PWR/32 BWR. This gives 2.16 receipts/day based on PWR and 2.05 receipts/day based on BWR. Given the high degree of uncertainty in these figures, computations of waiting time and system productivity are based on a range of 1.5 to 2.5 rail casks per day.

The parameter T_T is the travel and service time component of a cask's cycle time. The service time does not require independent estimation, since it is (on the average) just $1/\mu$. (At-reactor service times are not estimated separately since our interest is in receiving facility queues. For purposes of cask fleet estimation, the at-reactor service times are assumed to be included in travel time.) The travel time for a cask is a function of the distances and speeds characteristic of the disposal system. Based on current candidate repository sites, distances from the mass-weighted reactor centroid range from 1200 to 2360 miles (Ref. 2). A value of 1500 miles was used for computing T_T. Rail cask speeds have been estimated at from 72 to 288 miles per day for single car shipments (Ref. 1 and 2). A speed of 150 miles per day was used for this paper, giving a round trip travel time of 20 days. (Although T_T is a random variable, its expectation can be used alone in computing expected W_Q, since the model [2] "accounts for" the randomness in the traffic.)

RESULTS

Using the estimated values for the parameters derived above, Eq. 7 yields estimates of waiting time for any given number of casks in the system. By varying the number of casks, total systems productivity can be altered. Table I displays results of this kind for a range of parameters including the best guesses developed above.

TABLE I

Summary of System Performance Measures for Typical Parameter Values

Casks Per Day	Casks (n)	MTU Per Year	$E(L_Q)$ Casks	L_Q/N (%)
1.5	30	2266	1.99	6.6
1.5	40	2699	5.88	14.7
1.5	50	2881	12.27	24.5
1.5	60	2956	19.74	32.9
2.0	30	2403	0.81	2.7
2.0	40	3089	2.22	5.6
2.0	50	3570	5.59	11.18
2.0	60	3821	11.39	19.0
2.5	30	2453	0.43	1.4
2.5	40	3224	1.04	2.6
2.5	50	3920	2.39	4.8
2.5	60	4450	5.36	8.9

where;
n = number of casks in fleet
MTU/Year = system throughput
E(LQ) = expected value for length of input queue
LQ/N = expected value for length of input queue (percent of fleet).

The most basic result of this analysis is that for parameter values close to the center of our estimated range, system throughput rates at current design levels can be achieved without excessive queueing. For example, a service rate of two rail casks per day requires a fleet of 39 casks to provide the nominal 3000 MTU/year of system throughput. At this traffic level, the average queue length at the receiving facility is just over 2 casks, or about 5% of the fleet. At the lower value of 1.5 casks per day for service rate, 60 casks are required, and the average queue length for a system throughput level of 3000 tons is about 20, or 1/3 of the fleet.

Within the constraints of a given service rate, cask fleet size and typical queue length increase first slowly and then rapidly as throughput is increased. Taking the situation above (with $\mu = 2$, $N = 39$) as an illustration, adding four casks to the fleet (an increase of about 10%) yields a productivity increase of just over 7.5%, and increases the average queue length by about 47%. The next increment of 10% in the cask fleet size would give a productivity increase of about 6.4%, and an average queue length increase of about 49%.

This decreasing average and marginal productivity of the cask fleet is graphically illustrated in Fig. 2.

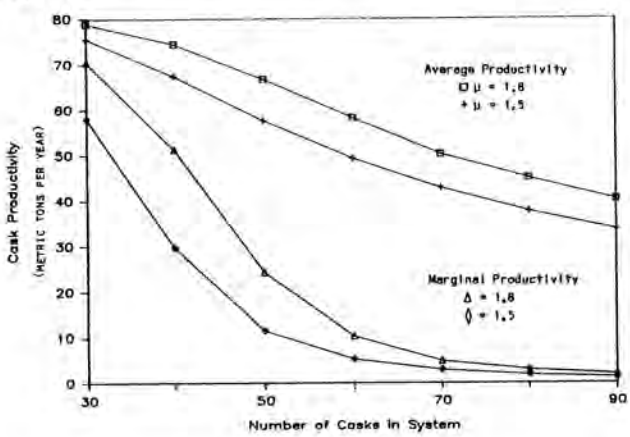

Fig. 2. Cask productivity.

This plot shows the gradual decrease in average productivity (measured in tons per cask year) that occurs when fleet size is increased, and the more rapid decrease in marginal productivity.

The marginal productivity curves are essentially "demand curves" for casks at any system service rate - they measure the contribution to throughput of an additional cask when service rate is held constant. The decline in marginal productivity can be quite dramatic. In the case for $\mu = 1.5$, it falls from 55 tons/year to 30 tons per year when the cask fleet increases from 30 to 40.

If the system throughput rate is held constant at the same level, Equation [7] may be used to define various combinations of service rate and cask fleet *that* will "just" satisfy the throughput level. This yields "isoquants" which define the potential for trading-off service capability for cask fleet size or vice versa. Figs. 3, 4 and 5 illustrate such curves for throughput rates of 2000, 3000, and 4000 tons per year.

Since the isoquants show how much service rate we would be willing to sacrifice to get an increment of fleet capacity or vice versa, they furnish marginal rates of substitution for the two resources. By a well known principle of optimization, the minimum

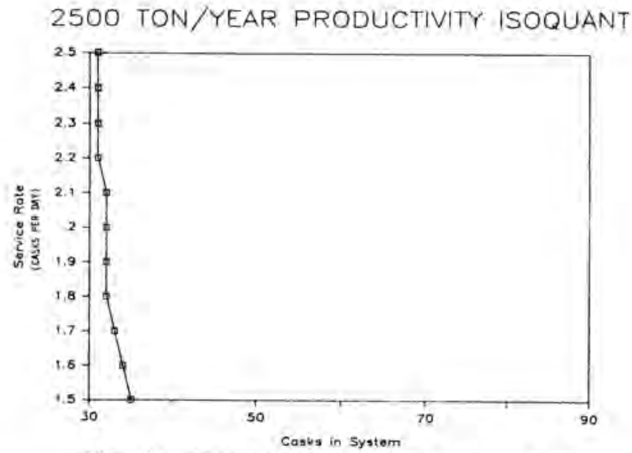

Fig. 3. Isoquant for system productivity.

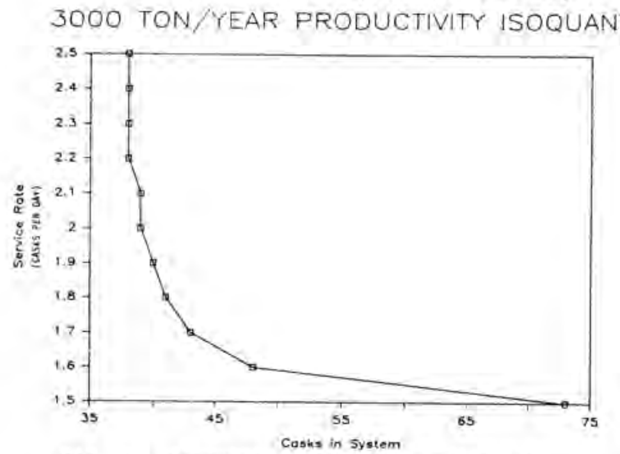

Fig. 4. Isoquant for system productivity.

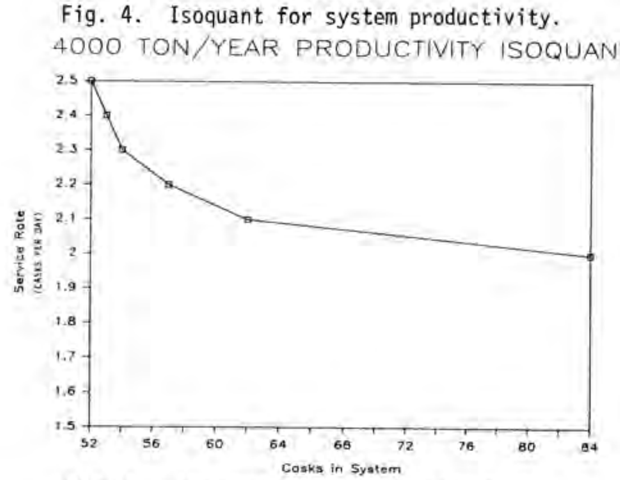

Fig. 5. Isoquant for system productivity.

cost combination of service rate and casks fleet size will be found where the system's internal rate of substitution is equal to the market price ratio.

Although the data used to generate these isoquants are very preliminary, the marginal rate of substitution shown in Fig. 4 is fairly constant in the vicinity of our best guess at the parameter ($\mu = 2.0$). The slope of the isoquant at this point is about 8-10 casks of fleet capacity per (cask/per day) of service rate capability.

Although cost information for both the cask fleet and receiving and handling facilities is still preliminary, some estimates exist. These rough estimates permit a crude comparison of marginal price ratios with the marginal productivity ratios above.

The marginal cost of a TTC "reference" rail cask is currently estimated at 2.5 million dollars (Ref. 1). The cost of an increment of receiving and handling facility has not been directly estimated, but current cost models of the repository facility allow approximation of such a value. These models, developed for estimating system life cycle costs (Ref. 2), are of the form;

$$C = C_o + C_1\left(\frac{V}{V_o}\right) + C_2\left(\frac{R}{R_o}\right)^{\alpha} + C_3\left(\frac{L}{L_o}\right) \qquad [8]$$

where

C = total cost
C_o, C_1, C_2, C_3 = cost equation parameters
V, V_o = total fuel volume in the repository subscript o indicates the reference design.
R, R_o = annual receipt rates (tons/year)
L, L_o = emplacement period (years)
α = a scale parameter for receipt rate related costs.

The marginal costs of receipt rate capacity are then;

$$\partial C/\partial R = \alpha \frac{C_2}{R_o^{\alpha}} R^{\alpha - 1} \qquad [9]$$

Using data from Ref. 2, C_2 varies from 1.1 billion to .45 billion, depending on the geologic medium selected for a repository. R_o is the reference repository receipt rate of 3000 tons per year. Since we are interested in the value of $\partial C/\partial R$ in the vicinity of this reference rate, we also take R = 3000 tons/year. The parameter α is an "economy of scale" parameter. For $\alpha = 1$, total cost is a linear function of receipt rate -- there are neither economies nor diseconomies of scale. Values of α less than one give various degrees of scale economy. While no detailed design sensitivity studies have been conducted to estimate the parameter α, experience with large capital projects suggests it is in the range of .6 to .8 (Ref. 5). Values from .4 to 1.0 were used to estimate marginal costs of receiving and handling facility capability, as shown in Table II.

TABLE II

Estimated Incremental Cost of 1 Cask/Day of Receiving Capacity -- Millions of 1984 Dollars

Scale Parameter (α)	Cost Coefficient Co/(Billions)				
	.4	.6	.8	1.0	1.2
.4	80	120	160	200	240
.6	120	180	240	300	360
.8	160	240	320	400	480
1.0	200	300	400	500	600

The figures in Table II show that the uncertainty in the scaling coefficient α and cost equation parameter C_o combine to produce quite a wide range of estimates for the incremental costs of receipt rate capacity. Values of \$80 million/cask/day to \$600 million/cask/day are possible. (These figures are expressed in casks/day but reflect $\partial C/\partial R$ evaluated at 3000 MTU/year.)

Even with this wide range of possible values for the incremental costs of receipt rate capacity, the comparison of price ratios to marginal productivity ratios is revealing. Even the minimum value of \$80 million per cask per day gives a price ratio greater than the marginal productivity ratio as shown in [10].

$$\frac{\partial C/\partial R}{\partial C/\partial N} > \frac{\text{MIN }(\partial C/\partial R)}{\text{MAX }(\partial C/\partial D)} = \frac{80}{2.5} > \frac{T/R}{T/N} = 10 \qquad [10]$$

Expression 10 shows that, beginning at our nominal 3000 ton year productivity, with a 2 cask per day receipt rate and a fleet of 39 casks, increasing productivity by adding receipt rate capacity is roughly three times as costly as increasing capacity by adding to the cask fleet. (Since about 8-10 casks will substitute for 1 cask/day of service rate). Naturally, the larger values of $\partial C/\partial R$ from Table II make this comparison even more conclusive. The corollary to this finding is that our assumed system mix of receipt rate capacity and cask fleet is not a minimum cost mix <u>for the traffic and cask assumptions made here</u>. This qualification is emphasized in light of the very preliminary nature of the traffic and cost assumptions. If these assumptions turned out to be valid, we could optimize the cask fleet/receipt rate mix (for a rate of 3000 tons/year) by adding cask fleet and decreasing investment in the receiving facility. A rough approximation of this optimum point is found by locating the increase in cask fleet required to lower marginal productivity to about 1/3 of its nominal value (while remaining on the 3000 ton isoquant). This occurs for a receipt rate of about 1.6 casks per day and a cask fleet of 48 rail casks.

Based on the (conservative) assumptions that C_o = .4, α = .4, this approximately optimum point gives a system cost only a few (~8) million lower than the reference system. This is an essentially inconsequential amount in the context of conceptual design for a \$20 billion system. Higher values of C_o and/or α would give potential system savings of about \$140 million. Thus the importance of optimizing the cask fleet - receiving facility mix is very sensitive to the receiving and handling facility cost function.

When this cost function is better known, the approximate optimum (as found above) can be discarded in favor of a more rigorous optimum. This would be found by minimizing a cost function (Eq. 8 plus a cask fleet term), subject a constraint derived from Eq. 6.

QUALIFICATIONS

As noted several times in the analysis, many assumptions and preliminary data values were used to illustrate the application of the queueing model to an economic trade off problem in system design. While these assumptions and data are in our opinion the best available, they are far too preliminary to warrant conclusions about the optimal cask fleet and service rate mix at this time. The type of analysis illustrated here needs to be pursued with more refined data. In this spirit the following comments are offered on what we feel to be the principal data uncertainties.

Arrival Time Distributions

There is a serious question whether the arrival time distribution is "stationary" over the course of a year. It is possible that the scheduling of reactor operations (and thus pool availability) is sufficiently correlated to produce seasonal peaks in the traffic intensity. This possibility could be investigated with data on cycle timing and a model of fuel selection for shipment.

Availability of Receiving and Handling Facility

The analysis in this paper assumes that required maintenance of the receiving and handling hot cells and equipment could be conducted in the periods when the equipment was idle. Failures of this facility should be accounted for in the estimation of the optimal receipt rate capacity. Incorporating this information in an analysis such as this would require more data from facility designers, and use of a more complete model in which facility failures are counted as presumptive priority "traffic" in the queue. The information gained in studying this question would also verify or serve to refine our preconceived notion about the service time distribution.

The analysis of a multimodel system would also require estimation of changes in the availability of this facility due to switching inloading setups.

Continuity of Cost Functions

The parametric repository cost function used here is an aggregated model for how repository costs behave in light of changes in major design and operating parameters. As aggregate functions, these are presented as smooth curves. In fact, the costs associated with receiving facility throughput rates may contain discontinuities (due to integral numbers of machines, cells, etc.). This cost function detail should be incorporated in the economic model.

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