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ECONOMIC IMPLICATIONS OF REACTOR DECOMMISSIONING FOR SPENT FUEL DISPOSAL

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Economic Implications of Reactor Decommissioning for Spent Fuel Disposal

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*Gene Heinze-Fry's work on the decommissioning aspects is appreciated, as is Nancy Birn's assistance and Joseph Baldwin's graphics. Chapman is Professor of Resource Economics in the Department of Agricultural Economics.

The New Draft Mission Plan[1] reopens the economic problem of the simultaneous storage of nuclear power waste fuel and decommissioned reactor material. DOE now proposes that the first Western repository will accept waste for permanent geologic storage in 2003 rather than 1998. A temporary facility, the Monitored Retrievable Storage plant proposed for Tennessee, now assumes greater importance by permitting the possibility of DOE waste acceptance in 1998.

Paradoxically, lower quantities of waste will to some degree lessen the attractiveness of a Federal permanent storage program. This is because the program has high fixed cost and considerable scale economies. Lesser quantities of waste can mean higher unit costs.

Civilian nuclear power waste was estimated at 126,642 MTU (metric tons uranium) in the 1986 reference case and 87,449 MTU if no new plants are ordered. The 1987 projection is a single value of 106,000 MTU.

Military waste to be stored is assumed equivalent to 8,000 MTU, and the material at West Valley is an additional 640 MTU. As a consequence, military waste increases from 6% in the 1986 reference case to 7% in the January 1987 projection.[2]

The decline in expected waste has two major causes. First, U.S. nuclear capacity has not grown as anticipated by DOE in earlier years. Figure 1 shows the history of U.S. capacity to date. As recently as 1980, the DOE Office of

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[1] U.S. DOE, Office of Civilian Radioactive Waste Management, "Draft Mission Plan Amendment," DOE/RW-0128, Jan. 1987, 55 pp.

[2] See 1987 Draft Mission Plan (supra) and USDOE-OCRWM, Analysis of the Total System Life Cycle Cost for the Civilian Radioactive Waste Management Program, DOE/RW - 0047, vols. 1 and 2, April 1986.

Nuclear Waste Management was anticipating as its median case that the U.S. would have 250 nuclear plants by 2000.[3/] Since each 1,000 MW-PWR plant generates about 5.3 billion kWh and creates about 27 MTU waste each year, declining nuclear capacity estimates translate directly into declining waste estimates.

A second factor in the lower estimate is the higher burn-up anticipated to produce more kWh per ton of fuel. However, this leads to more residual radioactivity per ton of waste. This, in turn, means higher waste handling costs per ton at the reactor and at any storage facility.

In the technical sphere, the dominant concept continues to be the feasibility of repository closure by filling corridors and shafts and demolition of surface buildings. This geologic closure of the full complement of projected waste fuel would apparently follow last waste acceptance by about 50 years for each site.

However, the Waste Management Program has a difficult triad of obligations: full public information and discussion; safe handling of waste for up to 100,000 years; and acceptance for storage in 1998. Hence, S. Fred Singer's argument for continued at-reactor interim storage.[4/] (Singer apparently favors reprocessing.)

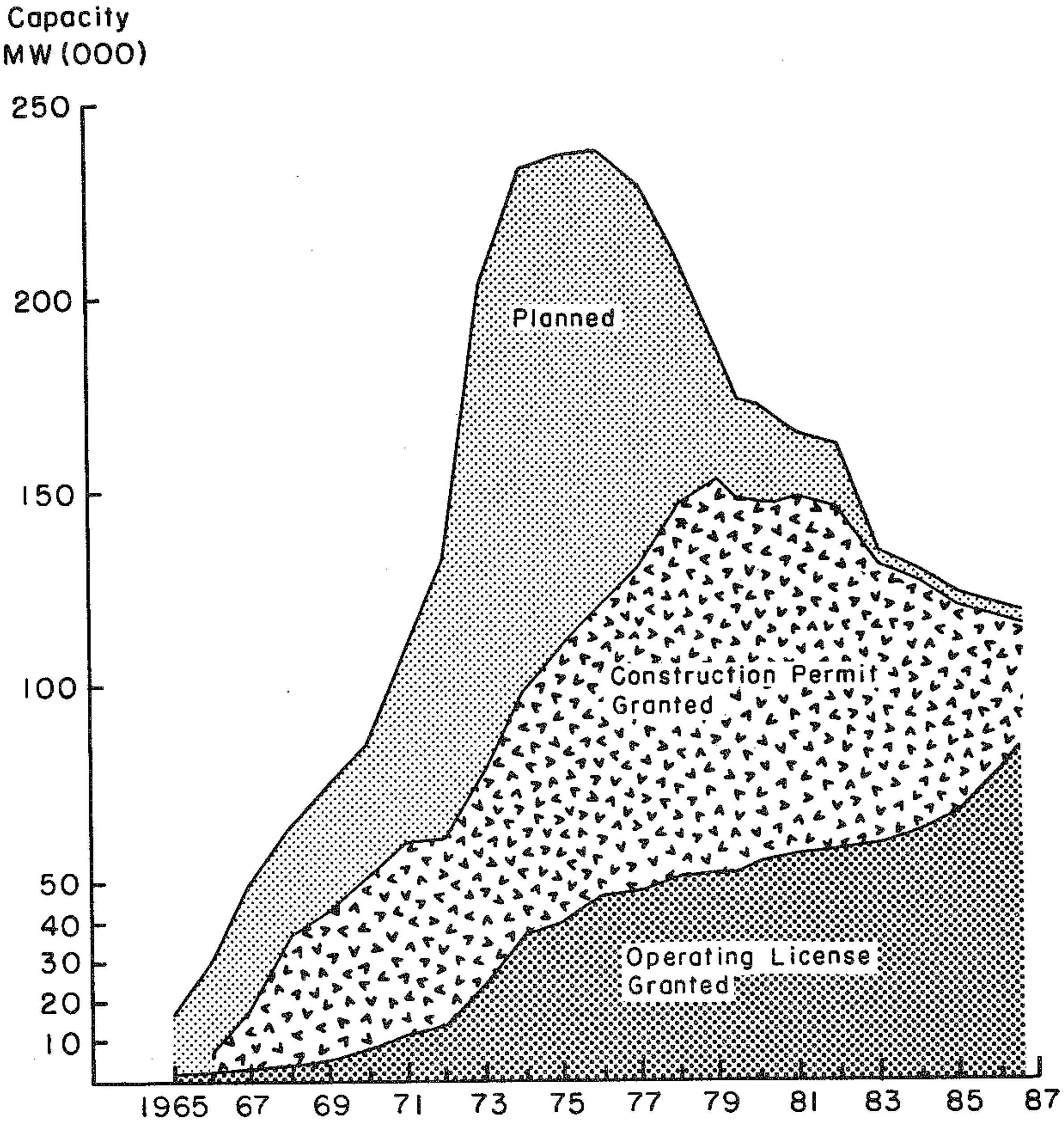
If prompt decontamination and dismantlement of reactor systems is taken as a national policy, there is an understandable reluctance to use these same sites for indefinite waste fuel storage. This leads to decommissioning economics.

In the first section of this paper, spent fuel storage costs are reviewed.

[3/] Using 1,000 MWe as equivalent to one unit. The 250 GWe (gigawatt electric) figure is from USDOE Office of Nuclear Waste Management, Final Environmental Impact Statement: Management of Commercially Generated Radioactive Wastes, DOE/EIS - 0046F, vols. 1, 2, and 3, October 1980.

[4/] S. Fred Singer, "High-Level Nuclear Waste Disposal," Letter, Science, 10 October 1986.

FIGURE I. U.S. NUCLEAR REACTOR CAPACITY, OPERATING AND PLANNED, 1965-1986



The second section summarizes decommissioning economics. Policy implications are discussed in the final section.

WASTE FUEL STORAGE COST

An important economic consideration of the problem is the eternal nature of the time scale involved. OCRWM (Office of Civilian Radioactive Waste Management) identifies the two principal objectives of its site selection processes as

> (1) minimize the adverse health effects from the repository during the first 10,000 years after closure, and (2) minimize the adverse health effects from the repository during the period 10,000 to 100,000 years after closure. [5]

Of course the same objectives apply to at-reactor storage. Table 1 shows the rapid decline in radioactivity in waste through decay. After 100,000 years, the waste is dominated by plutonium-239 because of its 24,300 year half-life. For example: the 1986 no new plant orders case would have an ultimate accumulation of 87,400 MTU as waste, and about ½% would be plutonium-239. The 440 MT of plutonium would have fallen to about 25 MT. Although the waste fuel never[6] becomes non-toxic, it does decline to the level of uranium ore after 100,000 years.

The radioactivity curves are unchanged by location. Similarly, decay in heat discharge by waste fuel has the same general decay pattern. The question is which policy is least hazardous within a generally acceptable economic framework.

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[5] 1987 Draft Mission Plan, p. 20.

[6] "Never non-toxic" means within a million years. Uranium ore is about 99.8% non-uranium and .2 of 1% uranium. After 100,000 years, the waste is no more toxic than ore and much less hazardous than uranium itself. 1980 DOE vol. 1, pp. 3-37, 38.

Table 1. Rapid Decline in Radioactivity of Waste Fuel

One year after removal from reactor, there are about 2 million curies per MTU. The proportions remaining at subsequent periods are - - -

After	Percent Remaining is about - - -
2 years	50%
5 years	25%
10 years	15%
100 years	2%
200 years	4/10 of 1%
1,000 years	1/10 of 1%
100,000 years	2/1,000 of 1%

Source: 1980 DOE vol. 1, p. 1.4.

At-Reactor Storage

At-reactor storage is well understood; essentially all nuclear power waste ever produced is now stored at a reactor. One method of storage uses air-cooled casks, by-passing the typical 5-10 year swimming pool storage. We can use the Pacific Northwest Laboratory (PNL) study of at-reactor costs to estimate permanent or eternal costs by this method.[7/]

PNL examines a 15-year period for storing a total of 276 MTU of waste. (This might be the waste from a large unit having 18.4 MTU waste per year.) Initial capital cost is \$2.8 million, rising by \$1.05 million per year as new casks are installed. Operating costs including insurance rises to \$500 thousand per year.

Extending this to a 30-year operating life, the only figure that changes is that O&M rises to \$1 million annually by 30 years. Each of the 45 casks might be replaced every 100 years after initial use.

From these data, an illustrative cost calculation of infinite storage is possible:

$$(1) \qquad PV_{\infty} = \sum_{j=0}^{\infty} \frac{\sum_{t=1}^{30} \frac{K_t}{(1+i)^t}}{(1+i)^{100*j}} + \sum_{t=1}^{30} \frac{OM_t}{(1+i)^t} + \sum_{t=31}^{\infty} \frac{OM_{30}}{(1+i)^t}$$

PV_{∞} is the present value of the cost of at-reactor storage over an infinitely long period, K_t is capital investment in year t, and OM_t is annual operation and maintenance. The real, inflation-adjusted interest rate is i. For example, if i = 3.5%, inflation might be 6.0% per year and market interest 9%.[8/] The exponent 100 in the denominator of the capital cost term

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[7/] E.T. Merrill and J.F. Fletcher, Economics of At-Reactor Spent Fuel Storage Alternatives, Pacific Northwest Laboratory, PNL--4517, April 1983, Table A-6.

[8/] Inflation in the GNP deflator was 6.1% from 1976 to 1986. Utility new bond interest was 9% in early February 1987. The At-Reactor study assumed a 3.5% real interest rate, and expressed its data in 1982 dollars. Also included is a cask decommissioning estimate.

reflects an "eternal" 100 year cask replacement cycle.

The solution to Eq. (1) is $48 million in 1986 dollars.[9/] Given the 552 MTU, we have a present value cost of permanent cask storage of $87,400 per MTU. This is 3/100 of 1¢/kWh.

If at-reactor storage were to be implemented as national policy, we have the C_r line from the origin in Figure 2.

Central Repository Storage

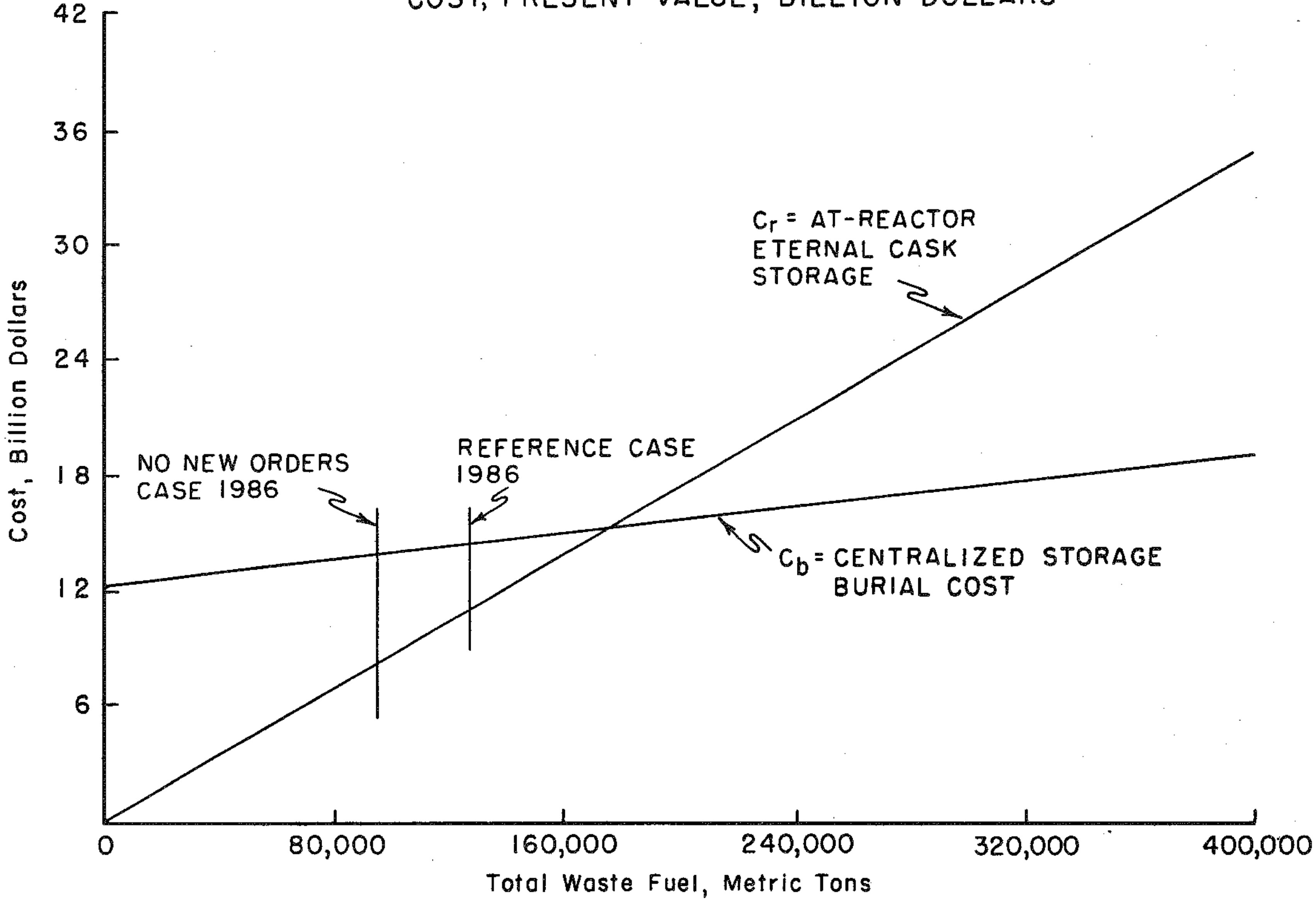
The repository program has a much different relationship of cost to quantity. Much of the repository program cost is fixed. This fixed cost includes siting, evaluation, mitigation, and administration. One interesting 1986 analysis reflects a 103-year cost projection for two repositories and a MRS facility. The MRS facility is planned for Tennessee. The basalt repository might be at Hanford, Washington, and the crystalline site is not specified.[10/] The sum of total costs without interest charges or discounting is $31.7 billion. With a 3½% real discount rate, the present value is $13.9 billion. This is the no new orders case, with 87,400 MTU developing by 2020. The calculations are shown in Appendix A.

In contrast, the reference case assumes renewed growth in nuclear capacity but provides for waste fuel acceptance only through 2020. In other words, the no new orders case has declining nuclear generation to 2020, while the reference case has accelerating generation at 2020. No recent planning material has been published that discusses waste storage for a growing nuclear industry.

[9/] GNP inflation was 14.5% from 1982 to 1986. The At-Reactor study used 1982$.

[10/] This is Case C-23 and B-4 from the 1986 Life Cycle Cost study. The locations are suggested in the 1987 Draft Mission Plan, pp. 33, 39. Text cost data are inflated 2.7% to 1986$ from the 1985$ used in the Life Cycle Report.

FIGURE 2. WASTE FUEL CENTRALIZED BURIAL AND ON SITE STORAGE COST, PRESENT VALUE, BILLION DOLLARS



This reference case estimate projects an undiscounted cost of $34.8 billion[11/] for storing 126,600 MTU at the same sites noted above. The present value is $14.5 billion. (See Appendix B.) The present values of the costs of the two repository estimates are similar because their costs are identical for the first 15 years and very similar well into the next century. Therefore the surprising result: a 31% reduction in total waste reduces the arithmetic sum of costs by just 9%, and reduces present value by only 4%.

Since both cases use the same repository sites and the Tennessee MRS, their estimates can be reproduced by this relationship:

$$C_b = 12.5 + \frac{.1615Q}{10^4} . \tag{2}$$

C_b is total waste burial cost, present value, in billions of 1986$.
Q is the total national quantity of waste fuel in MTU. The at-reactor storage policy is

$$C_r = \frac{.870Q}{10^4} . \tag{3}$$

Equations (2) and (3) and Figure 2 can be reformulated to express storage cost per kWh as a function of total nuclear generation for both options. These relations are

$$P_b = .0647 + \frac{12,500}{X} , \tag{4}$$

$$P_r = .349, \text{ all } X. \tag{5}$$

[11/] $33.9 billion in 1985$. Cases B-2 and C-11.

P_b is the cost or price of permanent repository burial in mills per kWh. Similarly, eternal or permanent at-reactor waste storage costs P_r, a constant .349 of a mill per kWh.

Figure 3 shows the economies of scale in projections for repository storage. At the end of 1986, about 14,200 MTU has accumulated at U.S. reactors, from nuclear generation of about 3.5 trillion kWh. Using two repositories and the MRS would cost about 3½ mills/kWh.

The new no orders case projects about 22 trillion kWh in cumulative nuclear generation. The cost would be about .6 of a mill/kWh, less than the current one-mill/kWh program charge. Nevertheless, at-reactor storage is always less costly.

Transportation may add a significant externality effect to economic considerations. Moving 126,600 MTU from reactors to permanent storage locations would, at an average 2,000 mile trip, mean 279 million ton-miles for waste shipment. Essentially, no waste has been shipped to date.

The economic incentive to proceed with centralized permanent burial may no longer be present. Permanent at-reactor storage seems less costly at the scale of the U.S. nuclear program now being considered.

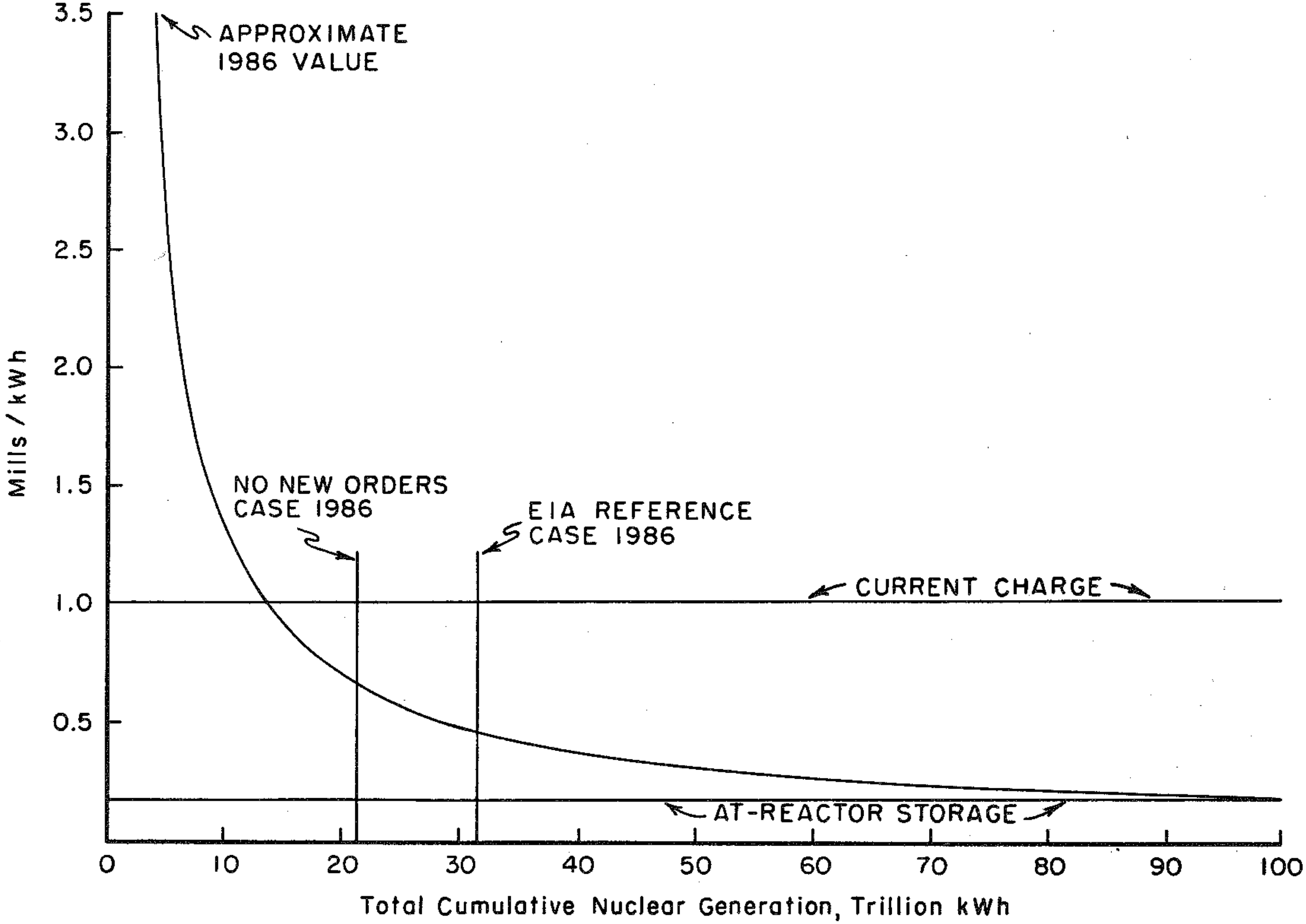
Reactor decommissioning policy becomes a major variable in waste fuel policy.

DECOMMISSIONING

Equations (6)-(9) represent a simple picture of the accumulation and decay of radioactivity in a normal reactor:

$$(6) \qquad \frac{dA}{dt} = \alpha G(t) - \delta A(t)$$

FIGURE 3. ECONOMIES OF SCALE, CENTRALIZED WASTE STORAGE



$\delta = \frac{+.693}{\varepsilon}$, the decay factor

ε = half-life for decay of radionuclide

A = current inventory of radionuclide at any time t

G = current generation at time t

α = parameter for radionuclide creation from generation

$\frac{dA}{dt}$ = current net change in inventory; creation less decay

(7) $$A = \alpha e^{-\delta t} \int_0^t e^{\delta t} G(t) dt,$$

(8) $$A = \alpha G \frac{1-e^{-\delta t}}{\delta}, \text{ if G is constant.}$$

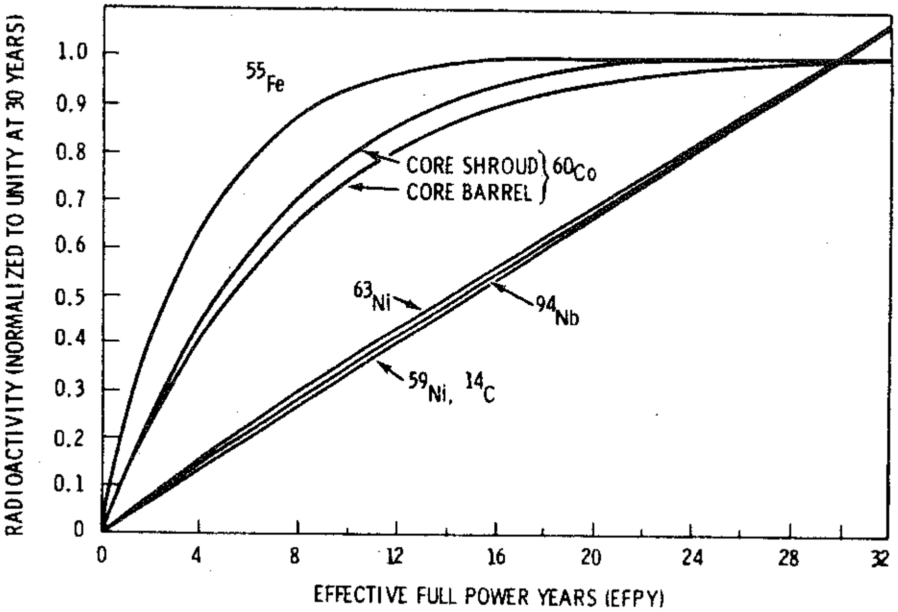
(9) $$A = A(k)e^{-\delta t}, \text{ after shutdown at k and t years after k.}$$

Figures (4) and (5) summarize the accumulation of radioactivity during the plant's normal operating life, and its subsequent decay. As with waste fuel in Table 1, decay is rapid after initial shutdown. However, low levels of long-lived elements make on-site or relocated storage a requirement for 100,000 years plus.

Decommissioning alternatives are conventionally described as three-fold. Decontamination or prompt dismantlement prepares a plant site for unrestricted access. This prompt dismantlement occurs immediately after reactor shutdown. Storage provides site maintenance and security while radioactive inventories decay. Entombment is a particular kind of on-site storage which can occur at any time after shutdown. This alternative buries the reactor and other contaminated materials in concrete.

We can present the basic economic logic of decommissioning alternatives with Equations (10)-(12).

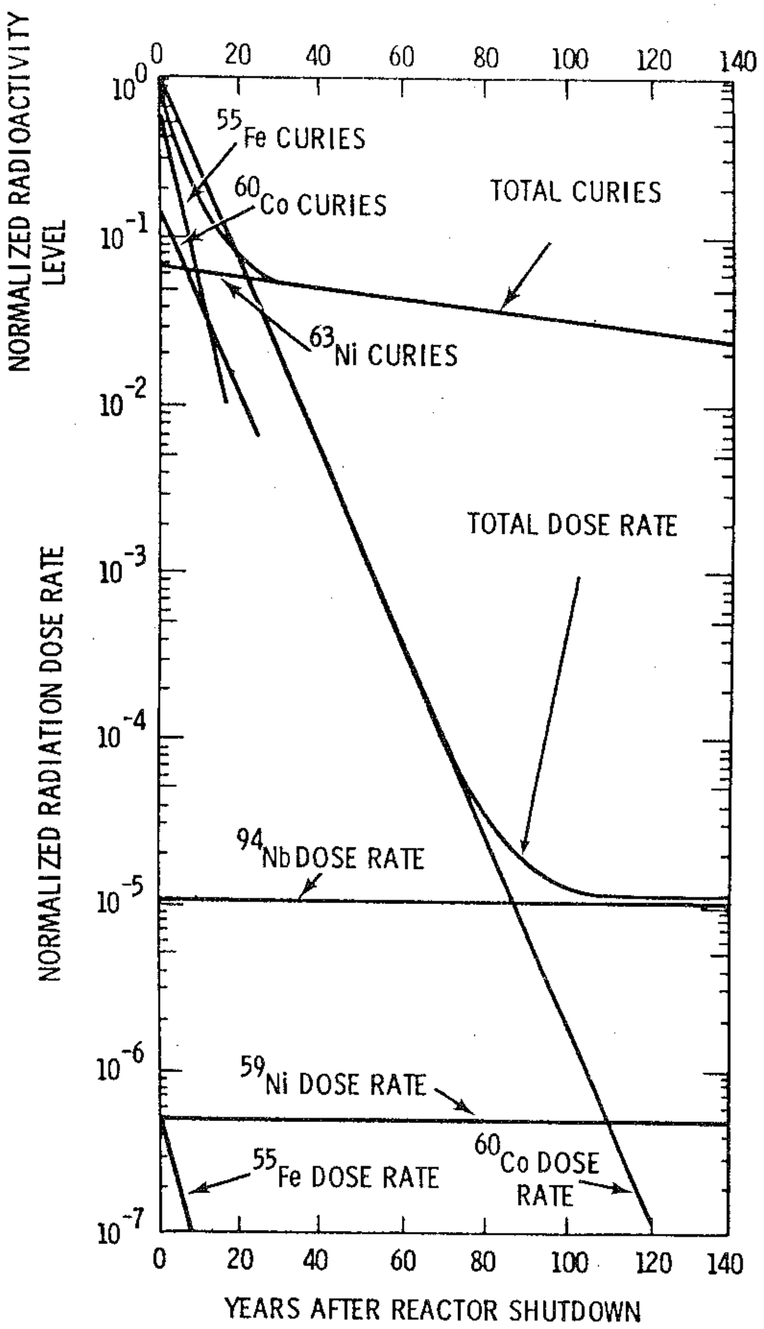
Figure 4



Buildup of Activation Products in PWR Vessel Internals as a Function of EFPY

Reproduced from NUREG/CR-0130, 1:p. 7-19.

Figure 5



Time Dependence of Radioactivity
Levels and Radiation Dose Rates
in the Activated Reactor Components

Reproduced from NUREG/CR-0130, 1:p. 7-39.

(10) $$C = \beta_0 + \beta_1 A(d) + \beta_2 S(d), \; 0 \leq d \leq \infty,$$

where C is the future cost of decommissioning for a reactor shutdown at date k. β_0 is a fixed cost that does not vary with radioactive inventories, and A is radioactive inventory at dismantlement date d. β_1 is a cost parameter which shows the dependence of dismantlement cost on radioactivity. S represents annual storage cost from shutdown at time k until dismantlement at time d. (Of course, S(t) might decline as A(t) declines.) β_2 is an economic term which gives the accumulated future value of the cost of d years of storage:

(11) $$\beta_2 = \frac{(1 + r)^d - 1}{r} .$$

The present value at shutdown year k of storage costs and future dismantlement at time d is

(12) $$PVC(k) = \frac{\beta_0}{(1 + r)^d} + \frac{\beta_1 A(d)}{(1 + r)^d} + \frac{\beta_2 S}{(1 + r)^d} .$$

Consider Eq. (12). It defines the present value of decommissioning. In economic terms, we want to find a value for the date d which minimizes decommissioning cost, and we want to know the present value of storage and dismantlement for dismantlement at d.

Remember that A (the inventory of radioactivity) declines at a decreasing rate in Figure 5. Ultimately, after tens or hundreds of thousands of years, it is essentially zero. It is immediately evident that $\beta_2 S$ must exceed β_0 if full dismantlement is ever economically preferred. In fact, if S/r is less than β_0 by a significant amount, dismantlement is never preferred. On a year by year basis, the economic decision is

(13a) If $r(\beta_0 + \beta_1 A(t)) > S(t)$, defer dismantlement.

(13b) If $r\beta_0 > S(t)$ for all $t > k$, never dismantle.

For example, suppose r is a 5% interest rate, fixed dismantlement cost is $300 million, radioactivity-sensitive dismantlement cost is $300 million * (.5)**(d/20), and storage is a constant $10 million. Complete dismantlement is never cost-effective, and perpetual storage saves $400 million present value[12/] compared to prompt dismantlement.

Dismantlement Estimates: Generic Studies

Generic estimates of reactor dismantlement have varied from the Battelle small reactor estimate of $17.5 million[13/] to my projection of a $3 billion average for prompt dismantlement of large reactors including those shutdown by severe accidents. The forty-four estimates are well characterized by a model which explains the variation in dismantlement estimates by assumed capacity, the date of the estimate, accident impact, the analyst, and Federal affiliation.

The results in Table 2 all have statistically significant coefficients and a R^2 of .87. In interpreting the Table 2 results, remember that the importance of a variable derives from the interaction of the estimated coefficient with the variable. The "t" statistics are a guide to relative importance.

Assumed accident impact is very important. This variable, before logarithmic transformation, is an index between 1 and 5. Thirty-seven of the generic estimates assume normal, accident-free operation. These are 1 on the

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[12/] The present value of eternal storage is derived from the last term in Eq. (12) and β_2 defined in Eq. (11). The present value of eternal storage is $200 million for $d = \infty$ and $S = \$10$ million annually. Prompt full dismantlement at $d = 0$ costs $600 million. Differentiating Eq. (10) with respect to d replicates the text discussion.

[13/] "Economic Aspects of Nuclear Plant Decommissioning," by Chapman, Heinze-Fry, and Mount (in preparation) describes both the 44 generic estimates and the 152 plant estimates. All dollar values are 1985$.

Table 2. Statistical Analysis of Dismantlement Estimates: 44 Generic Studies

$$\text{Dismantlement Cost} = e^{\beta_0} X_1^{\beta_1} X_2^{\beta_2} \ldots X_n^{\beta n}$$

No.	Variable Descriptions	Coefficient Values	"t" statistics
0	constant	-6.35	-3.0
1	capacity, megawatts	+0.93	+4.6
2	year of estimate, from 1956	+1.32	+2.3
3	accident impact	+1.18	+8.5
	Analyst Variables		
4	LaGuardia, $X_4 = 1$	-1.60	-4.0
5	Chapman 1984, $X_5 = 1$	+2.13	+4.3
6	Analysis & Inference, high, $X_6 = 1$	+2.11	+5.0
	Federal Affiliation		
7	Neither NRC, DOE, or Battelle, $X_7 = 1$	+1.41	+5.4

$R^2 = .874$, adjusted $R^2 = .850$

index scale. The other estimates are indexed by their accident severity.

Capacity is an important variable. The coefficient of 0.93 means a 10% increase in size increases the generic decommissioning estimate by 9.3%. This means that Table 2 has essentially no scale economies.

The year of the estimate is significant. For a 1981 estimate, 25 years from 1956, $X_3 = 25$. For the same analyst examining the same capacity in 1986, $X_3 = 30$ and we anticipate a 27% increase,[14] in 1985$.

Surprisingly, reactor type was not a statistically significant factor in the generic studies. It is important, however, in the reactor-specific estimates discussed below.

LaGuardia's are significantly lower than the other generic estimates. Two estimates (mine and the high Analysis and Inference value) are each identified by separate category variables. Other things being equal, the 2.13 coefficient for Chapman, X_5, means my value is 8.4 times higher than others in the sample.[15]

Finally, estimates made without Federal affiliation are much higher.

Table 2, then, provides a statistical way of predicting the results of recent generic studies. Suppose we consider a generic 1000 MW unit without accidents which is the subject of a 1985 estimate by a Federal agency. The Table 2 model predicts this estimate will be $91.7 million in 1985$.[16] An estimate 15 years later in 2000 would have a $159.0 value. An index 5 level accident would raise the estimate to $1.1 billion.

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[14] (30/25)**1.32 = 1.27.

[15] Tim Mount points out that these single-observation category variables result in perfect identification, and the other coefficients reflect variations in the data for the other 42 observations.

[16] For the equation in Table 2, $X_1 = 1{,}000$; $X_2 = 29$; $X_3 = 1$; $X_4 = 0$; $X_5 = 0$; $X_6 = 0$; $X_7 = 0$.

Specific Plant Estimates

An analysis of 153 specific plant estimates gives somewhat different results. In Table 3, the capacity coefficient is only 0.14: a 10% difference in size will mean only a 1.4% difference in the predicted dismantlement estimate. The year of estimate is less important.

A new factor in Table 3 is construction cost. The +0.13 coefficient implies that units with a 10% cost difference will differ by 1.3% in dismantlement estimates. Although reactor type was not significant in analyzing the generic estimates, Table 3 shows a BWR estimate would be expected to be 11% higher with other factors constant.

Another variable, age of reactor at time of estimate, is not shown in Table 3. Reactor age and calendar year of estimate appear to be very highly correlated with each other, and models with either perform with comparable adequacy and give similar average predictions.

The TMI accident variable X_5 is used to identify a single value, the $1.3 billion (1985$) reported for decontamination. (Recall this technique removes the TMI-2 observation from the data set for estimating coefficient values.)

The generic study model in Table 2 and the specific site model in Table 3 can be compared by examining predicted dismantlement estimates. Assume the same characteristics as above, and located in New York. The result is $92.0 million for the specific unit estimates, vs. $91.7 for the generic estimate model.

An estimate 15 years later would be $128 million. A TMI-2 accident would increase the dismantlement estimate to $2.5 billion.

Table 3. 153 Specific Unit Dismantlement Estimates

$$\text{Dismantlement Cost} = e^{\beta_0} X_1^{\beta_1} X_2^{\beta_2} \ldots X_n^{\beta n}$$

No.	Variable Descriptions	Coefficient Values	"t" statistics
0	constant	-0.18	-0.2
1	capacity, megawatts	+0.14	+2.9
2	year of estimate, from 1956	+0.80	+3.1
3	construction cost, million 1985$	+0.13	+3.1
4	BWR, X_4 = 1	+0.11	+1.9
5	Three Mile Island accident, X_5 = 1	+2.96	+9.1
6	LaGuardia estimate, X_6 = 1	+0.37	+5.5
7	Arkansas site, X_7 = 1	-0.58	-3.5
8	California site, X_8 = 1	+0.41	+4.7
9	New England site, X_9 = 1	+0.25	+2.7
10	New Jersey site, X_{10} = 1	+0.40	+2.7

$R^2 = .647$, adjusted $R^2 = .622$

Shutdown Modes and Decommissioning Alternatives

The general assumption is that a nuclear unit will operate normally for 30 years. Table 4 reports the causes and mode of shutdown and the planned decommissioning policy for all shutdown commercial nuclear power plants.[17/] Prompt decontamination and dismantlement has been undertaken for only one unit of the 8 which have been closed. It seems to be a difficult problem to extrapolate from this experience to the likely decommissioning choice for all of the country's reactors. Nevertheless, of those units actually closed, 88% are not decontaminated.

Any unit which is stored or entombed is potentially a site for waste fuel storage.

Dismantlement Waste Volume

The waste fuel program has been undertaken independently of Federal policy on decommissioning. The presumption apparently has been that dismantlement waste would go to low level waste sites. However, such sites have not been identified for large scale national dismantlement programs.

The anticipated volume of dismantlement waste can be separated into two components. The first factor is waste from reactors not experiencing severe accidents. The second factor is waste from reactors with core-melt accidents. For no-accident units, prompt dismantlement and decontamination is expected to require the relocation of 19,000 MT of waste with 1,400 rail shipments.[18/]

[17/] These are units at least 50 MWe, built and operated by utilities for sales to their retail customers.

[18/] NUREG/CR-0130, pp. G-26 to G-35 and p. 1-11, and LaGuardia, 1986, PG&E.

Table 4. Reactor Shutdown Modes and Decommissioning Alternatives

Reactor Name	Capacity	Generation History First Year	Last Year	Duration Years	Apparent Economic Shutdown Mode	Decommissioning Alternative
Shippingport	72 MWe	1957	1982	25	depreciation, high production cost	decontamination
Dresden 1	220 MWe	1960	1978	18	maintenance economics	storage
Indian Point 1	275 MWe	1962	1974	12	safety economics: no ECCS	storage
Humboldt Bay	65 MWe	1963	1976	13	safety economics: earthquake protection	storage
Hallam	76 MWe	1963	1964	1	maintenance economics	entombment
Pathfinder	58 MWe	1966	1967	1	maintenance economics	storage
Fermi 1	61 MWe	1966	1971	5	severe accident	storage
Three Mile Island 2	961 MWe	1978	1979	1	severe accident	storage

Sources: NUREG/CR-0130 and personal communications. See Chapman et al.

Notes: Commercial operation generally coincides with the year of first generation. Formal shutdown status may occur some years after last generation. Capacity shown is installed capacity when unit first generates electricity. ECCS means emergency core cooling system.

Let us assume that a TMI-2 type accident has an order of magnitude increase: 190,000 MT of waste.

One expectation of the number of severe accidents is given by this relationship:

(14) Probable number = RYS * Pr [core melts per RY].

Light water reactors in the U.S. have experienced one core melt in 1,082 reactor-years of operation through 1986.[19/] The experience ratio is $9.2*10^{-4}$. With 128 units now planned, and an assumption of a planned 30-year operational life, Eq. (14) gives 3.5 as the probable number of core melts for U.S. light water reactors.

For the 124.5 accident-free units, we would expect about 2.37 million metric tons of dismantlement waste. For 3.5 core melts, the figure is 665,000 MT. The combined sum is 3 million metric tons, moving by 223,000 rail shipments. If ultimate disposal relocation averages a 1,000 mile trip, the magnitude of transportation of dismantlement waste is on the order of 3.3 billion ton miles (U.S. tons).

If dismantlement waste is relocated at a waste fuel repository site at an average distance of 2,000 miles from each reactor, 6.6 billion ton miles are involved.

CONCLUSIONS

The volume of dismantlement waste (on the order of 3 million MT) and of waste fuel (about 127,000 MTU) represents between 3½ and 7 billion ton miles.

[19/] There were 989 reactor years of LWR operation through 1985 (Chapman *et al.*, Table 7), and an estimated 93 RYs in 1986 (September 1986 *Monthly Energy Review*).

Transportation planning for waste fuel should take into account the public reaction to dismantlement waste. It seems to me that political considerations could lead to a binary option: either both wastes are relocated to a few national storage areas, or both wastes remain at existing nuclear plant sites.

The health physicists may need to redo the dose analyses in this context.

Estimates of dismantlement cost continue to increase regularly. This is presumably due to several factors: greater volumes of material in newer reactors; more complex safety systems in newer reactors; accumulation of radioactivity in operating units; continuing unavailability of sites for acceptance of dismantlement waste.

In economic terms, deferring dismantlement is less costly as long as the potential interest on deferred dismantlement exceeds another year of on-site storage. The economic cost in terms of present value may be less for permanent storage than for full dismantlement and decontamination at any date.

Several factors combine to create incentives for long run or permanent reactor storage: natural radioactive decay; economics; and the unavailability of waste areas to accept large volumes of transported dismantlement material.

With the current uncertain status of the waste fuel program, the same three incentives exist to store spent fuel at existing reactor sites.

There is clearly a strong interaction: if either relocation program is indefinitely postponed, the logic for proceeding with the other program is minimal.

APPENDIX A. Annual and Discounted Costs for Life Cycle Cost Study Case C-23.

Note: No new reactor orders, 87,400 MTU total accumulation of waste fuel, an initial basalt Hanford geologic repository, a generic high cost crystalline second geologic repository, and a Tennessee Monitored Retrievable Storage facility.

	---- 1985 dollars, millions ----			
date	year	amount	discount factor	discounted amount
1983	1	226	0.966	218.36
1984	2	284	0.934	265.12
1985	3	305	0.902	275.09
1986	4	493	0.871	429.62
1987	5	665	0.842	559.91
1988	6	754	0.814	613.38
1989	7	668	0.786	525.04
1990	8	640	0.759	486.02
1991	9	429	0.734	314.77
1992	10	415	0.709	294.20
1993	11	648	0.685	443.84
1994	12	984	0.662	651.19
1995	13	946	0.639	604.88
1996	14	896	0.618	553.53
1997	15	822	0.597	490.64
1998	16	667	0.577	384.66
1999	17	502	0.557	279.72
2000	18	389	0.538	209.42
2001	19	338	0.520	175.81
2002	20	439	0.503	220.63
2003	21	865	0.486	420.02
2004	22	951	0.469	446.16
2005	23	912	0.453	413.40
2006	24	811	0.438	355.18
2007	25	756	0.423	319.90
2008	26	698	0.409	285.37
2009	27	642	0.395	253.60
2010	28	631	0.382	240.82
2011	29	622	0.369	229.36
2012	30	652	0.356	232.29
2013	31	682	0.344	234.77
2014	32	760	0.333	252.77
2015	33	582	0.321	187.02
2016	34	474	0.310	147.17
2017	35	483	0.300	144.89
2018	36	480	0.290	139.12
2019	37	461	0.280	129.09
2020	38	454	0.271	122.84
2021	39	581	0.261	151.88
2022	40	539	0.253	136.14
2023	41	461	0.244	112.50
2024	42	237	0.236	55.88
2025	43	205	0.228	46.70
2026	44	80	0.220	17.61
2027	45	82	0.213	17.44
2028	46	78	0.205	16.03
2029	47	71	0.199	14.09
2030	48	71	0.192	13.62
2031	49	71	0.185	13.16
2032	50	71	0.179	12.71

2033	51	71	0.173	12.28
2034	52	71	0.167	11.87
2035	53	71	0.161	11.47
2036	54	71	0.156	11.08
2037	55	71	0.151	10.70
2038	56	71	0.146	10.34
2039	57	71	0.141	9.99
2040	58	71	0.136	9.65
2041	59	71	0.131	9.33
2042	60	71	0.127	9.01
2043	61	71	0.123	8.71
2044	62	71	0.118	8.41
2045	63	71	0.114	8.13
2046	64	71	0.111	7.85
2047	65	71	0.107	7.59
2048	66	90	0.103	9.29
2049	67	90	0.100	8.98
2050	68	90	0.096	8.68
2051	69	90	0.093	8.38
2052	70	90	0.090	8.10
2053	71	90	0.087	7.82
2054	72	90	0.084	7.56
2055	73	90	0.081	7.30
2056	74	90	0.078	7.06
2057	75	90	0.076	6.82
2058	76	103	0.073	7.54
2059	77	103	0.071	7.29
2060	78	103	0.068	7.04
2061	79	103	0.066	6.80
2062	80	103	0.064	6.57
2063	81	103	0.062	6.35
2064	82	103	0.060	6.13
2065	83	103	0.058	5.93
2066	84	103	0.056	5.73
2067	85	103	0.054	5.53
2068	86	103	0.052	5.35
2069	87	103	0.050	5.16
2070	88	103	0.048	4.99
2071	89	103	0.047	4.82
2072	90	103	0.045	4.66
2073	91	103	0.044	4.50
2074	92	103	0.042	4.35
2075	93	103	0.041	4.20
2076	94	103	0.039	4.06
2077	95	103	0.038	3.92
2078	96	103	0.037	3.79
2079	97	103	0.036	3.66
2080	98	87	0.034	2.99
2081	99	99	0.033	3.29
2082	100	96	0.032	3.08
2083	101	119	0.031	3.69
2084	102	117	0.030	3.50
2085	103	81	0.029	2.34
2086	104	59	0.028	1.65

2087	105	0	0.027	0.00
2088	106	0	0.026	0.00
		30862.00		13522.67

APPENDIX B. Annual and Discounted Costs for Life Cycle Cost Study Case C-11, 126,600 MTU Waste.

This is Case C-11, MRS, basalt, generic high cost with the reference assumption of 126,600 MTU waste.

	---- 1985 dollars,	millions ----		
date	year	amount	discount factor	discounted amount
1983	1	226	0.966	218.36
1984	2	284	0.934	265.12
1985	3	305	0.902	275.09
1986	4	493	0.871	429.62
1987	5	665	0.842	559.91
1988	6	754	0.814	613.38
1989	7	668	0.786	525.04
1990	8	640	0.759	486.02
1991	9	429	0.734	314.77
1992	10	415	0.709	294.20
1993	11	648	0.685	443.84
1994	12	984	0.662	651.19
1995	13	946	0.639	604.88
1996	14	896	0.618	553.53
1997	15	822	0.597	490.64
1998	16	668	0.577	385.24
1999	17	503	0.557	280.27
2000	18	391	0.538	210.50
2001	19	339	0.520	176.33
2002	20	441	0.503	221.63
2003	21	872	0.486	423.42
2004	22	966	0.469	453.20
2005	23	920	0.453	417.02
2006	24	816	0.438	357.37
2007	25	758	0.423	320.75
2008	26	694	0.409	283.73
2009	27	593	0.395	234.24
2010	28	591	0.382	225.56
2011	29	595	0.369	219.41
2012	30	606	0.356	215.90
2013	31	638	0.344	219.62
2014	32	686	0.333	228.16
2015	33	665	0.321	213.69
2016	34	685	0.310	212.68
2017	35	686	0.300	205.78
2018	36	701	0.290	203.17
2019	37	656	0.280	183.70
2020	38	637	0.271	172.35
2021	39	640	0.261	167.30
2022	40	629	0.253	158.87
2023	41	553	0.244	134.95

2024	42	318	0.236	74.98
2025	43	320	0.228	72.90
2026	44	322	0.220	70.87
2027	45	328	0.213	69.75
2028	46	367	0.205	75.41
2029	47	316	0.199	62.73
2030	48	248	0.192	47.57
2031	49	71	0.185	13.16
2032	50	71	0.179	12.71
2033	51	71	0.173	12.28
2034	52	71	0.167	11.87
2035	53	71	0.161	11.47
2036	54	71	0.156	11.08
2037	55	71	0.151	10.70
2038	56	71	0.146	10.34
2039	57	71	0.141	9.99
2040	58	71	0.136	9.65
2041	59	71	0.131	9.33
2042	60	71	0.127	9.01
2043	61	71	0.123	8.71
2044	62	71	0.118	8.41
2045	63	71	0.114	8.13
2046	64	71	0.111	7.85
2047	65	71	0.107	7.59
2048	66	90	0.103	9.29
2049	67	90	0.100	8.98
2050	68	90	0.096	8.68
2051	69	90	0.093	8.38
2052	70	90	0.090	8.10
2053	71	90	0.087	7.82
2054	72	90	0.084	7.56
2055	73	90	0.081	7.30
2056	74	90	0.078	7.06
2057	75	90	0.076	6.82
2058	76	117	0.073	8.56
2059	77	117	0.071	8.28
2060	78	117	0.068	8.00
2061	79	117	0.066	7.72
2062	80	117	0.064	7.46
2063	81	117	0.062	7.21
2064	82	117	0.060	6.97
2065	83	117	0.058	6.73
2066	84	117	0.056	6.50
2067	85	117	0.054	6.28
2068	86	117	0.052	6.07
2069	87	117	0.050	5.87
2070	88	117	0.048	5.67
2071	89	117	0.047	5.48
2072	90	117	0.045	5.29
2073	91	117	0.044	5.11
2074	92	117	0.042	4.94
2075	93	117	0.041	4.77
2076	94	117	0.039	4.61
2077	95	117	0.038	4.46

2078	96	117	0.037	4.30
2079	97	117	0.036	4.16
2080	98	117	0.034	4.02
2081	99	117	0.033	3.88
2082	100	90	0.032	2.89
2083	101	101	0.031	3.13
2084	102	123	0.030	3.68
2085	103	105	0.029	3.04
2086	104	95	0.028	2.65
2087	105	74	0.027	2.00
2088	106	86	0.026	2.24
2089	107	62	0.025	1.56
SUMS		33912		14138.93

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