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The Eternity Problem in the Economics of Nuclear Waste Storage: Centralized or On-Site?

by

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Abstract

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Continuing the current moratorium on new nuclear plant orders reduces the amount of expected nuclear waste, and raises the possibility that centralized storage may not have an economic advantage over on-site storage. This paper reviews projections on nuclear power growth and termination, waste production, and cost functions for centralized and on-site storage. Reactor waste policy is reviewed as it affects fuel waste policy. The conclusion finds the current one-mill fee to be adequate in 1988 dollars for either policy, and argues that there is currently no economic advantage for either centralized or on-site storage.

The Eternity Problem in the Economics of Nuclear Waste Storage: Centralized or On Site?

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The effective moratorium on new nuclear plant construction has an impact upon the amount of spent fuel which is anticipated, and the economies of scale which accrued to a centralized storage program with an expanding nuclear industry are lesser with a diminished industry. Permanent on-site storage, with constant average costs, may now be economically competitive. In addition, the increasing possibility of permanent on-site storage of decommissioned reactors reduces the risk-avoidance motivation for spent fuel shipment to centralized repositories. This paper reviews the available data on nuclear waste storage. Projections of the amounts of waste fuel are related to projections of future use of nuclear power. Cost functions are derived for a centralized waste storage program with one location in Nevada and a second at an Eastern site. Cost functions for "eternal" storage on-site at reactors are compared to the centralized storage functions. Reactor waste policy is briefly reviewed because of its important implications for fuel waste policies. The conclusion

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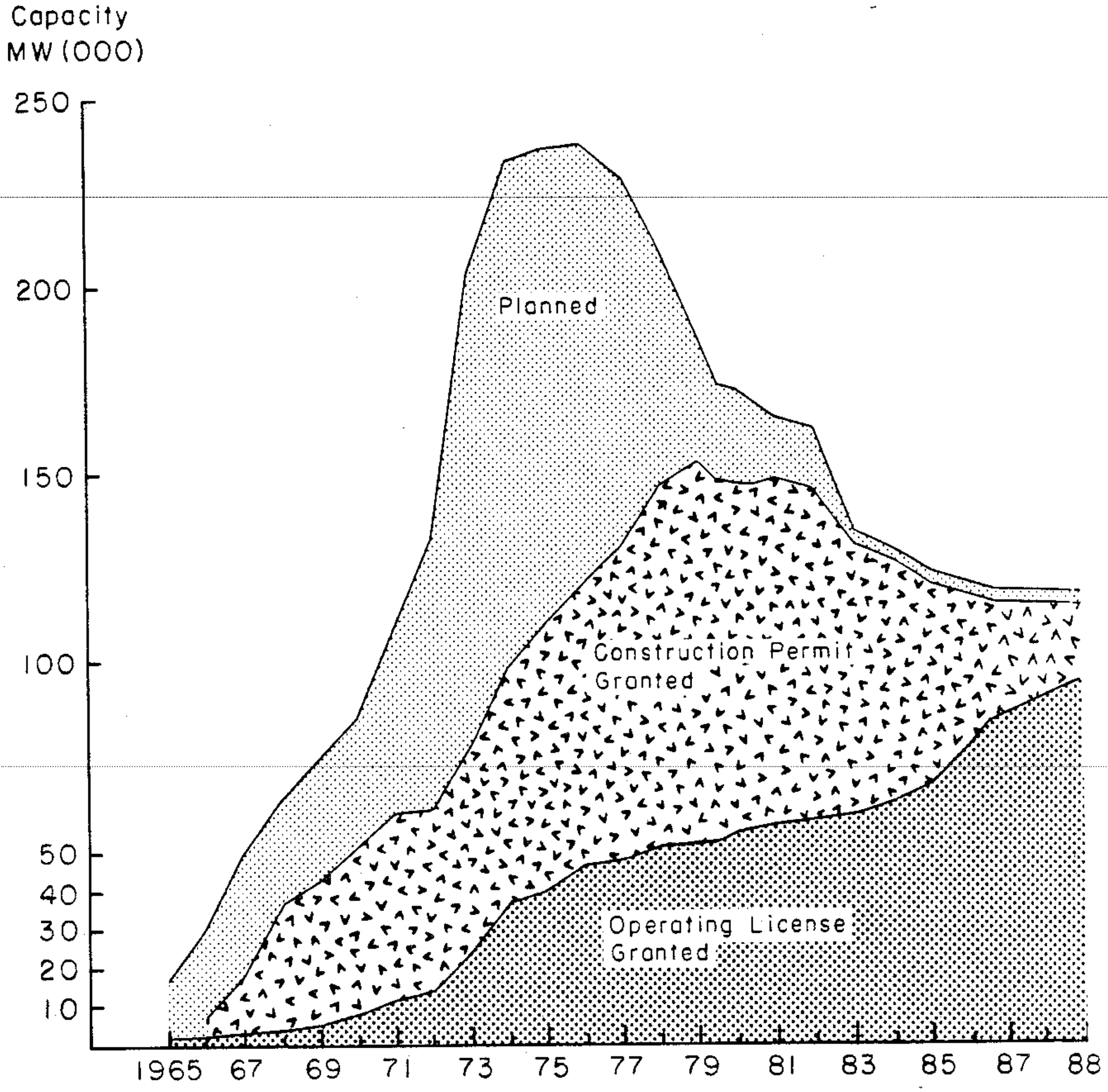
argues that the reduced scale of future nuclear generation eliminates the cost advantage of centralized storage.

I. THE CURRENT STATUS OF NUCLEAR POWER AND SPENT FUEL

The nuclear power industry has not attained the growth previously anticipated. In 1976, utilities had planned to build 234 reactor units with 236,000 MW (megawatt = 1,000 kilowatts) of capacity. No orders have been placed since 1978. By early 1988 (Figure 1), planned expansion has been reduced to a cumulative total of 125 reactors with a capacity of 117,000 MW.[1] Since each year's operation of a 1,000 MW plant produces about 25 MTU (metric tons uranium) waste, the scale of expected growth is the major determinant of the cumulative amount of material.[2]

Several offsetting uncertainties affect the capacity-waste relationship. First, the 10 civilian nuclear power units which have shut down permanently have done so without attaining the 30 years of full service originally anticipated. (See discussion below). As plants close prematurely, less cumulative waste per plant accumulates. Second, the currently projected total of 125 reactors includes the Seabrook unit, which may be closed, and seven other units which have been temporarily closed for 2 or more years. Any of this second group of 9 reactors which do not operate will reduce the cumulative waste which is projected. The third uncertainty implies that nuclear waste could be higher for given levels of electricity generation. The Office of Civilian Radioactive Waste Management (OCRWM) assumes each reactor will become more efficient, generating more electricity per unit of nuclear fuel. If this efficiency increase does not develop, there will be more waste for given generation levels than is currently projected.

FIGURE 1. U.S. NUCLEAR REACTOR CAPACITY, OPERATING AND PLANNED, 1965-1988



It might be expected that potential accidents would be a major uncertainty in estimating expected waste volumes. At Three Mile Island Unit 2, two million gallons of contaminated water await disposition as do 20 tons of fuel debris at the bottom of the reactor.[3] However, in this instance special plans have been developed which remove the unit from waste fuel planning.

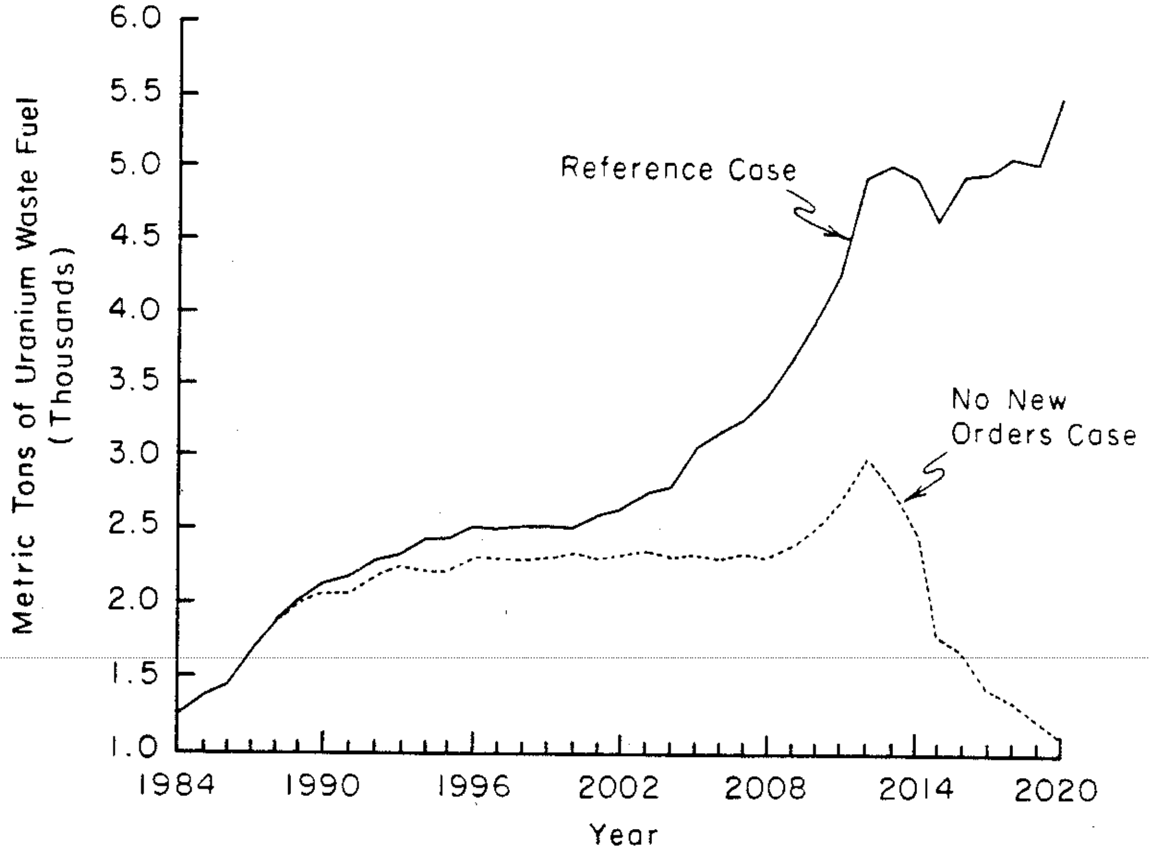
Figure 2 portrays expected annual production of fuel waste in the most recent published detailed analysis.[4] The reference case assumes a resumption of nuclear power expansion, reaching 248,000 MW of capacity by the end of the 2020 planning period. However, the no new orders case assumes a permanency of the past 10 years' lack of orders. In cumulative amounts, the expansion reference case reaches 126,642 MTU of waste in 2020, and is increasing by 5 MTU per year at that time. The no new orders case totals 87,449 MTU of waste, and annual production is declining to zero. (A metric ton is equivalent to 1.1 U.S. tons).

It should be emphasized that the two cases differ dramatically in their implication for nuclear waste after 2020. The reference case is accelerating in nuclear plant operations and waste production at the end of the period. With the no new orders case, the nuclear era is essentially concluded as the last reactors are closed.

In both cases, military waste equivalent to 8,000 MTU of spent fuel is included within the totals. The 640 MTU of spent fuel deposited at West Valley, New York is excluded from both cases.

At present, spent fuel is stored at reactor sites for all reactors except the West Valley material. This cumulative amount is 17,000 MTU in mid 1988.[5]

FIGURE 2. ANNUAL SPENT-FUEL GENERATION, TWO CASES



Source: <u>Life Cycle Cost</u>, p. 16.

II. ECONOMIES OF SCALE IN CENTRAL REPOSITORY STORAGE

The basic outline of current policy as viewed by the Department of Energy's Office of Civilian Radioactive Waste Management (OCRWM) is to develop a repository at Yucca Mountain, Nevada. This location is north of Death Valley and borders both the Nevada Test Site and the Nellis Air Force Range. The Test Site is the major location for testing nuclear weapons and is partially contaminated. The Nellis base currently uses bombing and gunnery areas north and west of the proposed waste storage site.[6] Presumably, military activities that might be hazardous to a repository would cease or be relocated if the repository is developed.

Current legislation enacted in December 1987 authorizes OCRWM to study this Yucca Mountain site for development of the first repository. The authorization for proceeding with a second eastern repository now is cancelled, but the need for it may be formally considered between 2007 and 2010.[7]

The legislation provides special cash payments to American Indian tribes or states that agree to be hosts. After waste storage begins, Nevada would receive $20 million annually, and the tribe or state hosting a Monitored Retrievable Storage Facility (MRS) would receive $10 million annually.[8] There is no indication yet that these potential payments have excited the interest of potential hosts.

In addition to cancelling the Eastern repository, the new legislation leaves the status of temporary MRS unresolved. Two motivations for an MRS remains. A temporary MRS in the East would reduce exposure to radioactivity from the transport of waste fuel. Without an MRS, the typical truck shipment of spent fuel would travel 2,000 miles from an Eastern reactor to the Yucca Mountain site.[9] A second motivation is that an MRS would permit Federal acceptance of utility waste while the Yucca site was being completed.

The central repository concept has assumed that when a repository reaches a maximum of, for example, 70,000 MTU, it is closed, filled, sealed, and marked.[10] No further security is anticipated.

An important physical factor affecting waste storage economics is the decay rate curve for radioactivity. Table 1 represents the 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 87,449 MTU as waste, and about 0.5 of 1% might be plutonium-239. The 440 MT of plutonium would have fallen to about 25 MT. Although the waste fuel never becomes non-toxic, it does decline to 70% of the toxicity level for ingestion of uranium ore after 100,000 years.[11] The radioactivity curves are unchanged by location whether centralized or on reactor sites. Similarly, decay in heat discharge by waste fuel has the same general decay pattern.

For the repository program, much of the cost is fixed and includes siting, evaluation, mitigation, administration, closure, and decommissioning. To compare a centralized program with an at-reactor program, I have selected the cases representing a first repository at the Yucca Mountain location, a temporary MRS facility perhaps in Tennessee, and a generic eastern location for the second permanent repository. For the reference case for an expanding industry, the sum of total costs is $28.5 billion in 1988 dollars before discounting. This is the generally higher cost curve in Figure 3. In contrast, the sum of the cost projection for the no new orders case is $26.4 billion for the lower curve in Figure 3. Suppose we discount the cost streams with a 3.5% real interest rate, representing, for example, a 4% inflation rate and a 7.5% interest rate. The present value amounts are $13.1 billion for the expansion

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: See Office of Nuclear Waste Management, p. 1-4.

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case with 126,642 MTU by 2020, and $12.7 billion for 87,449 MTU in the no new orders case.

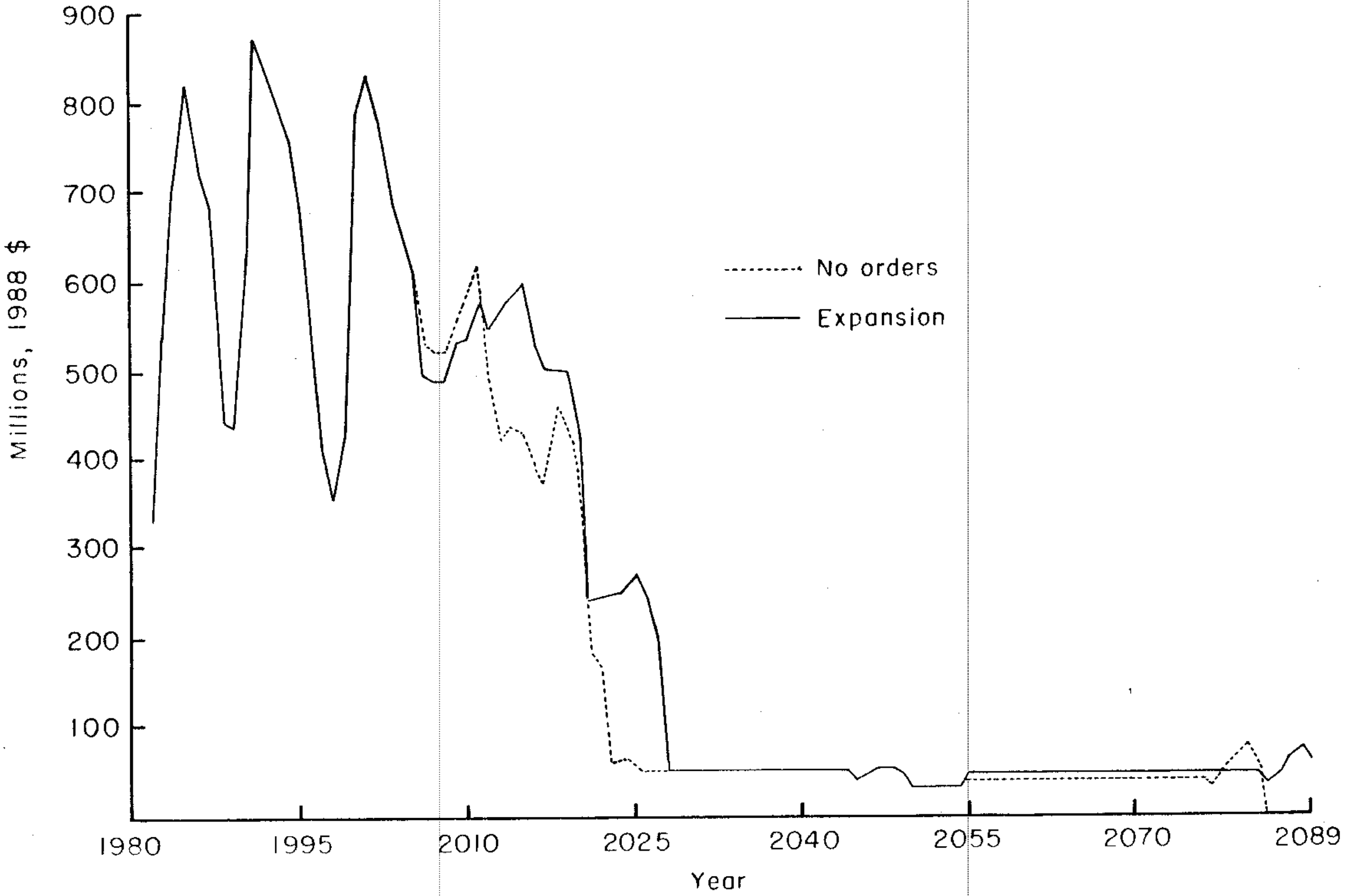
Adding 45% to the accumulated waste fuel total causes only an additional 3% in present value cost. This is because the two cost curves are identical for 30 years, and discounting gives little economic significance to the cost differences which emerge later.

The estimates can be reproduced by these total and average cost relationships:

$$[1] \qquad TC_b = \$11.8 \text{ billion} + \$10{,}600\ Q,$$

$$[2] \qquad AC_b = \$10{,}600 + \frac{\$11.8 * 10^9}{Q},$$

FIGURE 3. COST PROJECTIONS: NO ORDERS AND EXPANSION CASES, 1983-2089



where TC_b is total cost of waste burial in dollars; Q is waste in MTU, and AC_b is average cost of burial in dollars per metric ton of waste. Equation [2] can in turn be reformulated to define average cost per kWh for waste burial:

$$[3] \qquad P_b = .0513 + \frac{11.8 * 10^{12}}{G}.$$

P_b is expressed in terms of mills per kWh and G is generation.[13] (A mill equals one-tenth of a cent.) While [3] is average cost, note that marginal cost is a very low one-twentieth of a mill per kWh. This is rather astounding, reflecting the high fixed costs and low incremental costs reported above. For the no new orders case with 87,449 MTU waste projected, the average cost is 0.7 mills per kWh, and the marginal cost of additional waste is 0.05 mills per kWh.

III. COST OF AT-REACTOR STORAGE

As noted, all the U.S. civilian spent fuel ever produced is now stored at a reactor with the exception of the 640 MTU now at West Valley. One method for at-reactor storage uses air-cooled casks, bypassing the typical 5-10 year swimming pool storage. We can use the Pacific Northwest Laboratory study of temporary at-reactor costs as a basis for estimating permanent or eternal costs by this method.[14]

Pacific Northwest 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 \$5 million, rising by \$1.4 million per year as new casks are installed. Operating costs, including insurance, rise to \$600,000 per year.

In extending this 15-year analysis to a 30-year reactor operating life, operating costs (OM) rise to \$1.2 million annually by 30 years. Each of the 45 casks needed to store the full 30-year amount of 552 MTU might be replaced every 100 years after initial use.

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

$$[4] \qquad PV = \sum_{j=0}^{\infty} \frac{\sum_{t=1}^{30} \frac{K_t}{(1+i)^t}}{(1+i)^{100*j}} + \sum_{t=1}^{30} \frac{OM_t}{(1+i)^t} + \sum_{t=31}^{\infty} \frac{OM_{30}}{(1+i)^t} .$$

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, 3.5% inflation-adjusted interest rate is i. The exponent 100 in the denominator of the capital cost term reflects an "eternal" 100 year cask replacement cycle.

The solution to Equation [4] is \$51 million in 1988 dollars. Given the 552 MTU, we have a present value cost of permanent cask storage of \$92,000 per MTU.

Pacific Northwest has estimated material and security costs for fuel waste storage during the initial period after removal from the reactor. Radioactivity and thermal discharge are at their highest during this initial period, and both decay as discussed. Consequently, each subsequent storage period had a cost which is no higher than that of prior periods. The initial period estimates serve as an upper boundary of later period cost.

As with centralized storage, at-reactor storage cost can be reformulated into total and average cost functions and expressed in mills per kWh.

[5] $TC_r = \$92,000\ Q,$

[6] $AC_r = \$92,000,$

[7] $P_r = .44.$

As with Eqs. [1] - [3], the TC and AC terms are again in dollars, and [7] defines the average cost of on site storage as .44 of 1 mill per kWh.

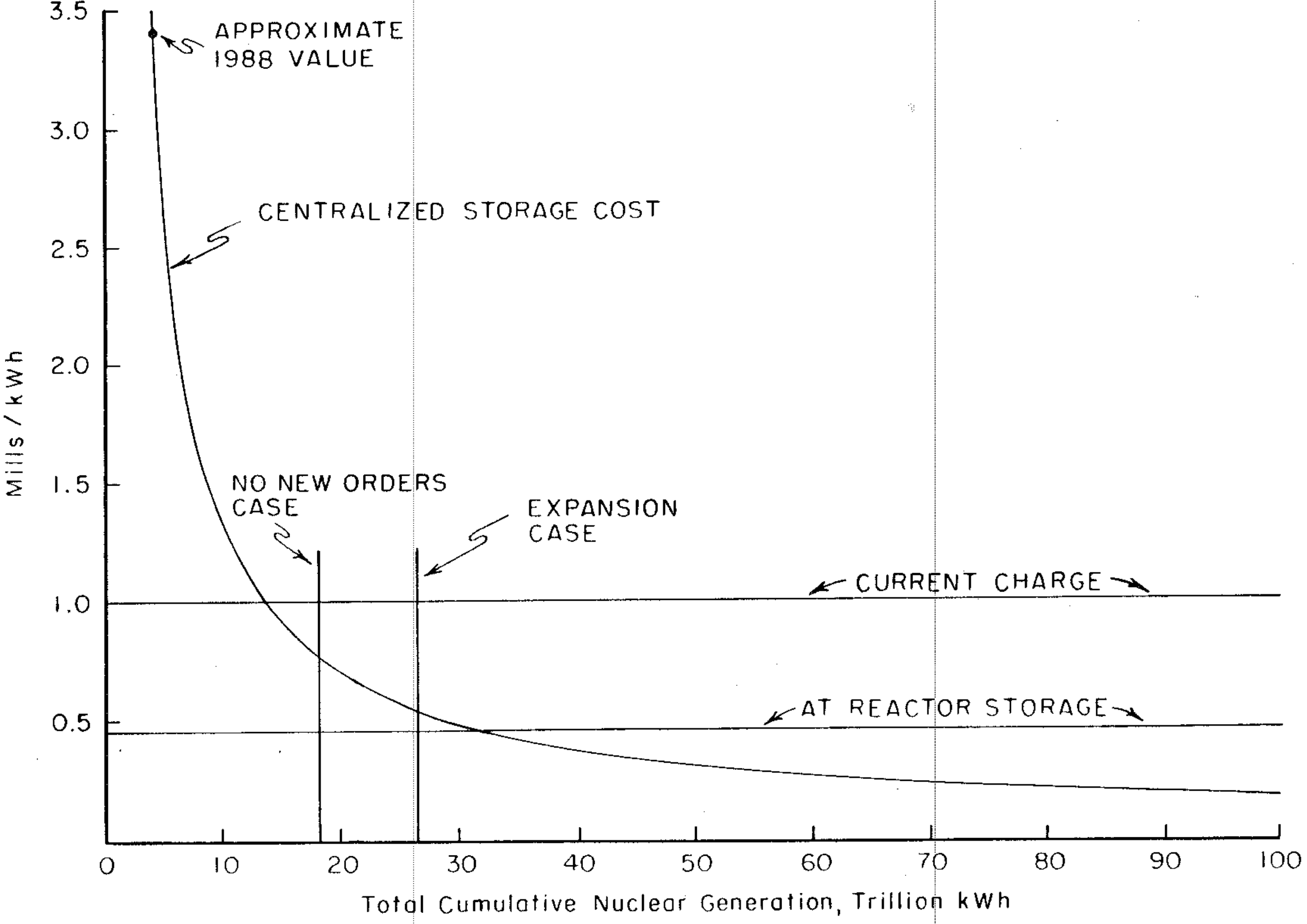
IV. COMPARISON

These results are summarized in Figure 4. Some interesting conclusions are evident. First, the 1988 value is 3.4 mills per kWh for centralized storage. This approximates the cost of centralized waste storage for the 3.5 trillion kWh of nuclear generation to mid 1988 which has produced about 16,700 MTU waste. If nuclear power generation were to cease in 1988, the magnitude of waste disposal costs which might be anticipated would be about $12 billion for centralized two-site storage or $1.5 billion for on site at-reactor storage.

Second, if the status quo continues with no new orders, at-reactor storage would be somewhat less costly than centralized storage. Third, the expansion case shows centralized and at-reactor storage about equal. Fourth, if nuclear generation were to grow very rapidly to use the full 140,000 MTU capacity of two sites, the average cost would decline to, but not fall below the at-reactor cost. (This is not shown in the Figure.)

Fifth, the current charge of 1 mill per kWh of nuclear generation appears to be satisfactory in 1988 dollars. This 1 mill fee is now collected by utilities from their customers and paid to OCRWM to cover the ultimate cost of fuel waste disposal. It does seem that it should increase over time at or near general inflation.

FIGURE 4. COMPARISON: CENTRALIZED AND AT REACTOR STORAGE



V. THE DECOMMISSIONING INTERFACE

Historically, waste fuel and reactor decommissioning have been viewed as distinctly different issues. Waste fuel has been termed high level waste, and its regulatory responsibility has rested with the Department of Energy's Office of Civilian Radioactive Waste Management. The decommissioning problem at the Federal level has been monitored by the Nuclear Regulatory Commission. Reactor waste disposal is defined as primarily low level waste.

In general, decommissioning has been seen as the full and immediate dismantlement of reactor material and its relocation at reactor waste storage sites. These sites would probably be general low level waste sites which would store medical, research, and industrial nuclear waste in addition to reactor waste.

Radioactivity decay in shutdown reactors is comparable in a qualitative way to that which applies to high level waste fuel. That is, much of the reactor waste hazard decays quickly, as does the fuel waste hazard in Table 1. Consequently, although prompt dismantlement after shutdown is generally thought to be the preferred policy, this is not in fact taking place. Table 2 shows the decommissioning status of the 10 commercial nuclear plants which have been closed. Of these 10 units, only the Shippingport reactor is being dismantled. The small size and simple design of Shippingport allow its major components to be lifted intact and placed on a ship for movement through the Panama Canal to ultimate storage in Washington. It remains to be seen if modern 1,000 MW plants can be so treated.

Since reactor waste and fuel waste are the focus of unresolved storage problems, and both become less hazardous over time, there is an obvious motivation for simultaneous rather than separable resolution of each problem. There is no merit to a large scale program for waste fuel transport and

Table 2. Reactor Shutdown Modes and Decommissioning Status

		Generation History				
Reactor Name	Capacity	First Year	Last Year	Duration Years	Apparent Shutdown Mode	Decommissioning Status
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
La Crosse	51 MWe	1969	1987	18	safety economics	storage
Three Mile Island 2	961 MWe	1978	1979	1	severe accident	storage
Shoreham	809 MWe	1986	1988	2	no evacuation plan	storage

Sources: NUREG/CR-0130; Chapman 1987; personal communications; Nuclear News.

Notes: Commercial operation generally coincides with the year of first generation, although obviously this is not the case with Shoreham. This unit generated power in low-power testing for two years. 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.

centralized storage if reactor waste remains at reactor sites. Similarly, shipping massive volumes of reactor waste while fuel waste remains in locus seems questionable.

As with the fuel waste program, the low level waste-reactor decommissioning policy lacks specific waste sites. No state has yet agreed to become the locus for reactor waste storage.[15] The nuclear industry journal summarizes a lengthy report with a headline: "LLW Siting: Is There Order Within the Chaos?"[16] Perhaps the biggest barrier to dismantlement is institutional.

There are political reasons to consider reactor sites as permanent or eternal storage locations. Political support for nuclear power has frequently been strongest amongst the groups employed at nuclear facilities or benefiting from their property tax contributions. These areas may have less objection to their becoming hosts for nuclear waste areas than those localities which opposed nuclear plant construction.

Multiple reactor locations should be particularly good candidates because of their large contiguous land areas and experienced security forces. There are 9 areas which have had 3 commercial reactor unit sites, and many more which have 2 reactors.[17] Because of their large nuclear capacity, each of these 9 areas generally have good transportation systems for moving waste (and new) nuclear fuel.

VI. CONCLUSIONS AND DISCUSSION

The United States is the location of one-third of the world's 295,000 MW capacity of currently operating plants. U.S. capacity exceeds the combined total of the second and third largest countries' capacity, that of France and Russia.[18] U.S. policy will affect waste planning in much of the world.

The primary policy focus with respect to U.S. fuel waste is the development of the Yucca Mountain site in Nevada as the first central underground repository. The original design contemplated a 70,000 MTU capacity which would ultimately be sealed, decommissioned, and left. To summarize, this capacity is more than sufficient to hold the mid 1988 level of approximately 17,000 MTU now residing at reactor locations. However, if one assumes a continuing industry with no new orders, the 87,449 MTU anticipated would, with past design criteria, require two central repositories. The second repository would be in an Eastern state.

The Office of Civilian Radioactive Waste Management desires to develop a short term Monitored Retrievable Storage facility to reduce population exposure to waste fuel transport and to shorten at-reactor storage time. Current legislation authorizes the continued study of this concept but not implementation.

With an expanding nuclear industry, new central repositories would need to be developed every 10-15 years. The planning horizon, however, has focused upon the amount of waste that would accumulate by a specific year, ignoring the accelerating amounts of waste that would continue to be produced.

Analysis of the OCRWM preferred system shows very low marginal cost and high fixed cost. Present value analysis shows therefore, major scale economies with average cost at 3.4 mills per kWh for current waste levels and asymptotically approaching one-half mill per kWh as nuclear generation approaches the 29 trillion kWh figure associated with the 140,000 MTU waste capacity of two repositories. The current 1 mill per kWh fee appears adequate for the centralized system if adjusted for future inflation.

At-reactor eternal storage is estimated to be just below one-half mill per kWh. (All dollar figures in 1988 dollars.)

We may conclude that, if the current absence of new orders continues, there is no overall economic advantage to centralized storage.

The decay curve for radioactivity in spent fuel has important economic implications. Two years after removal from a reactor, only 50% of the original activity remains. After 10 years, only 15% remains. But the nature of the long lived elements means that the overall rate of decay decelerates. After a century, 2% remains, and after 1,000 years the waste still retains 0.1 of 1% of its original radioactivity. Even after 100,000 years, the very low .002 of 1% is still sufficiently hazardous as to require segregation of the material. Hence the appropriateness of the "eternal" descriptor. At this point, after 100,000 years storage, the hazard is less than that contained in uranium ore.

The major facet of centralized storage versus at-reactor storage in this context is the question of abandonment. Current central storage plans call for the Nevada site to be filled, sealed, marked, and left 50 years after it reaches capacity. The "eternity problem" is left underground. At-reactor storage of fuel waste (or reactor waste) means eternally dedicating current surface reactor sites for waste.

The decommissioning interface raises serious problems which have not yet been recognized. Reactor waste exhibits the same form of decay as fuel waste. The decay is very rapid initially, but some components require the same eternal segregation. As with actual spent fuel, the "spent reactors" remain currently on site. Nine of the ten closed reactors are now in on-site storage. As with the centralized storage program for fuel waste, no sites have been accepted by host states for reactor waste storage.

One solution might be the dedication of existing multiple reactor sites as eternal waste locations. The 9 sites with 3 or more reactors are distributed throughout the country in areas with high concentration of nuclear capacity. Some form of regionalized storage for both fuel waste and reactor waste should be considered.

General attention to larger issues of nuclear power policy properly dominates scientific and public concern. Safety, accidents, and cost of construction for operating reactors are properly seen as more important than nuclear waste. Nuclear waste policy itself must consider several nonmonetary factors: transportation hazard, security against terrorists, contamination potential, and public attitudes for and against waste storage. This paper contributes one finding to the larger policy discussion: there is no cost advantage or other economic incentive for either centralized or at-reactor storage.

Footnotes

1. *Monthly Energy Review*, February 1988; Chapman, 1983, p. 218.
2. Technically, the amount of waste produced depends upon the type of reactor, the design burnup, thermal efficiency, and operating practice. For example, a typical 1,000 MW pressurized water reactor (PWR) with 31.6% thermal efficiency, 33,000 MWDt/MTU burnup, and 60% capacity factor would discharge 25 MTU of waste annually for most of its operating life. Detailed discussion is in USDOE-OCRWM (April 1986), Chapter 9, and USDOE-EIA, *Historical Plant Cost*, p. 225.
3. *Science*, 4 December 1987.
4. USDOE-OCRWM (April 1986), *Analysis of the Total System Life Cycle Cost for the Civilian Radioactive Waste Management Program*, volume 1, page 15 and volume 2, page A-1. Another OCRWM report without detail is the June 1987 fee adequacy report.
5. *Analysis of the Total System Life Cycle Cost for the Civilian Radioactive Waste Management Program*, *op. cit.*, Table B-1.
6. USDOE-OCRWM, *Environmental Assessment*: *Yucca Mountain Site*, May 1986, volume 1, pp. 2-1 and 3-33.
7. *OCRWM Bulletin*, December 1987/January 1988, p. 1.
8. Ibid., p. 2. A host tribe or state receives half these amounts after an agreement is signed until the waste arrives.
9. *Yucca Mountain Site*, pp. 7-96 and A-44.
10. *Analysis of the Total System Life Cycle Cost for the Civilian Radioactive Waste Management Program*, *op. cit.*, p. A-10.
11. See Office of Nuclear Waste Management, pp. 3-37, 38.

12. Cases C-20 and C-24 in <u>Analysis of the Total System Life Cycle Cost for the Civilian Radioactive Waste Management Program</u>, <u>op</u>. <u>cit</u>., inflated to 1988$ with the GNP index.

13. G equals 206.8 million kWh for each MTU, derived from the assumptions in note 2.

14. See Merrill and Fletcher.

15. Very different perspectives are found in <u>Nuclear News</u>, "Waste Management Update," March 1988, and Marvin Resnikoff's analysis.

16. <u>Nuclear News</u>, March 1988, p. 48.

17. <u>Nuclear News</u>, February 1988, pp. 63-82. The 3 reactor locations are in these eight states: New York (at Oswego and at Indian Point), Pennsylvania, South Carolina, Alabama, Arizona, California, and Washington.

18. See <u>Nuclear News</u>, March 1988, p. 86.

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