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FACTORS AFFECTING THE OPTIMUM FUEL CYCLE

D. E. Deonigi
and
E. T. Merrill

Battelle Memorial Institute
Pacific Northwest Laboratory
Richland, Washington

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FACTORS AFFECTING THE OPTIMUM FUEL CYCLE

Fuel cycle costs have been calculated over the years using a wide range of techniques developed by AEC laboratories, private industry, utilities and universities. The method of handling the various cost factors has improved over the years and has resulted finally in a situation where these techniques seem to have converged to the same effective answers. Certainly, the area of greatest uncertainty remains to be the handling of inventory and various forms of fuel financing.

To derive the optimum fuel cycle, it is first necessary that there be some consensus on the fuel cycle cost model so that a series of calculations using cost parameters which specifically apply to the situation being analyzed will result in a meaningful optimum. The first figure shows a list of some of the fuel cycle codes that are publically available which use different techniques for fuel cycle cost calculations, but when the input is reviewed to be sure that all parameters are equivalent, the fuel cycle cost calculated by each code is nearly the same and the working capital is responsible for the only variation in this cost. The first method listed is using the CINCAS code available in the Argonne Code Center which uses a present worth technique applied to all costs. A slight variation of this method on the pre-reactor inventory costs is applied to uranium. This code is a batch-oriented cost code. The second code, called QUICK, has been used in plutonium recycle analyses for many years. It uses a direct working capital calculation, and yields nearly identical costs. It is a batch-oriented code. The third code is called PACTOLUS, which is a multi-batch oriented code. However, for this

comparison the calculation was made using a succession of the same batch data, and as you see the costs are very nearly the same. It uses a present worth calculation but has available to it quite a range of methods for calculating taxes and depreciations. The fourth code on the list is called POWERCO. It does not have the ease of input that the other codes have, but is a present worth multi-batch oriented code very similar to the PACTOLUS code and yields nearly the identical answer. In the case of the present worth codes, the working capital was derived by using a present worth factor of 1 (0%) to obtain direct costs and then applying a present worth factor of 1.07 (7%) to obtain the total cost. The equivalent direct interest calculation was 14%. It is important that these codes agree over a range of exposures because with this basic agreement we can then derive a minimum cost under the assumption that a number of different computer codes will all result in the same effective answer.

The theoretical optimum fuel cycle can be calculated simply by determining the fuel cycle cost resulting from fuel operating to a given exposure without regard to control requirements and system load factors, etc. The total cost is broken down into cost components which can be classified into three basic types. They are shown on the second slide. The first is the net burnup cost, which is the cost of uranium depletion plus plutonium credits, which tends to be nearly constant with burnup. The second type includes those costs which are typically expressed in \$/kg, such as fabrication and reprocessing, which are not completely insensitive to exposure but can be considered independent. These costs decline rapidly with exposure in a hyperbolic fashion. The third component of cost is fuel inventory, which increases as fuel enrichment

increases to yield higher fuel exposure. This cost is shown as working capital carrying charges and is seen to increase with exposure. The resulting total of these three components usually defines a theoretically optimum fuel exposure.

From a fuel design standpoint it is desirable to approach but never exceed this theoretically optimum exposure; and further, because the area of the minimum is reasonably flat, other factors such as fuel technology and the electric generation needs of the utility should ultimately define the optimum fuel exposure. When the optimum fuel exposure exceeds the capability of the fabrication technology, then the incentive to improve this technology is determined by taking the difference in cost operating at the optimum point and comparing this with the technologically limited exposure.

Many parameters have influence on the optimum exposure; however, some have considerably more than others. In Slide 3 an examination of the relative importance of each fuel cycle parameter is shown. From this we can see that, although the cost of U_3O_8 affects the fuel cycle cost significantly, it has little influence on the optimum fuel cycle. The effect will be combined with an increase in plutonium price which moderates the cost increase and nearly doubles the effect on the fuel cycle. Changes in fabrication cost have substantial affect on both cost and the length of the fuel cycle. Changes in reprocessing cost have smaller effects since the expense occurs after the revenue is obtained. Note also that the charge rate for working capital has a strong influence on both fuel cycle cost and exposure. The load factor parameter, which has been frequently over estimated in evaluations of nuclear systems, is

seen to have a marked influence on the optimum exposure and also on the fuel cycle cost.

The fourth slide presents our present best guess at the future variations in the basic cost factors for the next 30 years. Obviously they will be subject to change as more information becomes available. Note that we are projecting a rise in U_3O_8 costs leveling off after 1991, coupled with rising plutonium price. The plutonium price continues to rise due to its value to fast reactors. Fabrication and reprocessing costs decrease due to the increased size of the industry. The effective cost of money is high in the near term and is then assumed to decrease somewhat, but not to the levels of the mid 60's. The load factor is assumed to rise as the plant matures and then decrease as more efficient plants are added to the system. This projection may also be high by ten percent or so in each period for many electric systems.

Slide five illustrates the relationship of exposure, generation requirements, and the fuel management scheme. Note that the quarter core relationship could also be obtained by reloading one-third core on 16 month intervals and the one-fifth core relationship could be obtained by reloading one-third core on 20-month intervals. A longer cycle time could be more economical since it does not take much longer to reload a larger fraction of the core. The potential availability of the plant is therefore increased. However, it is necessary to avoid a shutdown during a seasonal peak load period, and the refueling must be dovetailed into the maintenance schedule of the other plants on the system. In the usual case a 12 or 18 month schedule is desired.

Slide six shows the combined influence of the cost factors considered

previously and the generating requirements of the system. For the costs and loads assumed a fuel management scheme involving annual refueling of one-sixth of the core is valid for 25 years. For the 1996 to 2000 period a transition to reloading one-seventh of the core is indicated.

Slide seven presents similar data for a PWR indicating an acceptable fuel management scheme involving annual refueling of one-fifth of the core for the first 25 years. Again a transition to a smaller reload fraction is indicated in the 1996 to 2000 period.

Both of these last slides are based on a rather high load factor after the plants are 20 or 25 years old. This has not been true for fossil fired plants in the past and may not be true for nuclear plants either, but nuclear plant operating costs rise very rapidly at reduced loads since an expensive fissile inventory must be maintained if the plant is to be operated at any time during the year. Slide 8 illustrates this point. Note that the fuel cycle cost doubles as the load is reduced from 80% to 15% and doubles again at 5%. Thus it would seem that as a system expands a utility will purchase some type of peaking capacity to meet these peak loads rather than buy additional base load capacity which would compete with the nuclear plant.

The incremental cost curve on this slide approaches the subject from another point of view. Assuming a utility needed the nuclear plant to generate at 15% load factor, the fuel cycle cost for that energy would be over 3 mills per kWh, as seen on the total cost curve. However, their decision to buy more enrichment to produce more energy would be based on the incremental cost curve, and the competition is with plants having fuel costs in the 1.3 to 1.4 mill range, not the 2 to 3 mill range given

by the total cost curve. For this reason we believe the nuclear plants will operate at relatively high load factors or they will be retired from the system.

We have shown that there usually exists an optimum fuel exposure which results in minimum fuel cycle cost. This minimum can be used to calculate the economic incentive for technological improvements if the optimum exposure cannot be reached. Since costs do not increase rapidly at exposures less than the optimum, practical fuel management schemes can be derived to meet the needs of the electric system.

FUEL CYCLE COST COMPARISON

<u>Code</u>	<u>Direct Costs</u>	<u>Working Capital Costs</u>	<u>Total Cost</u>
CINCAS	1.25	1.11	2.36
QUICK	1.25	1.10	2.35
PACTOLUS	1.25	1.11	2.36
POWERCO	1.25	1.10	2.35

Figure 1

Figure 2

FUEL CYCLE COSTS

Fuel Cycle Cost, \$/kWh

Fuel Expense, \$/kWh $\times 10^{-3}$

	<u>Change in Fuel Cycle Cost</u>	<u>Optimum Fuel Exposure, MWD/MT</u>	<u>Change in Optimum Exposure, MWD/MT</u>
Reference Condition	0	29,500	0
\$1/lb Increase in U ₃ O ₈ Cost	+.085	29,230	- 270
\$10/kg Decrease in fabrication cost	-.063	28,620	- 880
1% Increase in Working Capital	+.062	28,400	-1100
10% Decrease in Load Factor	+.092	27,830	-1670
\$/g Fissile Increase in Pu Price	-.016	29,130	- 370

Figure 4. Effect of Fuel Cycle Parameters on
Optimum Cycle for BWRs

<u>Year</u>	<u>U₃O₈, \$/lb</u>	<u>Fabrication, \$/kg</u>		<u>Reprocessing, \$/kg</u>	<u>Plutonium Value, \$/g</u>	<u>Working Capital Rate</u>	<u>Load Factor Percent</u>
		<u>BWR</u>	<u>PWR</u>				
1971-75	7.00	75	90	42	7	14	75
1976-80	7.50	70	84	42	8	12	80
1981-85	8.00	65	78	35	9	12	75
1986-90	9.00	60	72	30	10	12	65
1991-95	10.00	55	65	25	12	12	50
1996-2000	10.00	55	65	25	14	12	40

Figure 4. Projected Fuel Cycle Factors

LOAD-EXPOSURE RELATIONSHIP FOR ANNUAL REFUELING (15 MW/MT)

Figure 6

Projected Fuel Exposure for BWRs
Starting up in 1970

<u>Year</u>	<u>Optimum Exposure, MWD/MT</u>	<u>Exposure Adjusted to Even Core Fraction</u>	<u>Annual Reload Core Fraction</u>
1971-75	29,500	29,600	1/6
1976-80	31,300	31,500	1/6
1981-85	29,600	29,600	1/6
1986-90	27,000	25,500	1/6
1991-95	23,200	19,700	1/6
1996-2000	20,100	18,400	1/7

<u>Year</u>	<u>Optimum Exposure, MWD/MT</u>	<u>Exposure Adjusted to Even Core Fraction</u>	<u>Annual Reload Core Fraction</u>
1971-75	35,100	33,000	1/5
1976-80	36,900	35,000	1/5
1981-85	34,100	33,000	1/5
1986-90	30,600	29,000	1/5
1991-95	25,700	22,000	1/5
1996-2000	22,500	21,000	1/6

Figure 7

Projected Fuel Exposures for PWRs Starting up in 1970

Figure .8

FUEL CYCLE COST
VS
LOAD FACTOR