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FUEL UTILIZATION IMPROVEMENTS IN A ONCE-THROUGH PWR FUEL CYCLE

FINAL REPORT ON TASK 6

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ABSTRACT

In studying the position of the United States Department of Energy, Non-proliferation Alternative Systems Assessment Program, this report determines the Uranium saving associated with various improvement concepts applicable to a once-through fuel cycle of a standard four-loop Westinghouse Pressurized Water Reactor.

Increased discharged fuel burnup from 33,000 to 45,000 MWD/MTM could achieve a 12 percent U_3O_8 saving by 1990. Improved fuel management schemes combined with coastdown to 60 percent power, could result in U_3O_8 savings of 6 percent.

Continued encouragement by the DOE to all concerned parties in implementation of cost-effective uranium savings concept is recommended.

ACKNOWLEDGMENT

The work reported here represents the efforts of many individuals. In particular, significant contributions were made by Linda Phelps and R. W. Miller in performing many of the calculations. R. A. George and J. M. Hellman provided input on the costs/schedules of RDD programs. D. R. Smith provided many helpful suggestions on the overall contents of the report.

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SUMMARY

Uranium savings associated with various improvement concepts applicable to a once-through fuel cycle were calculated for a standard four-loop Westinghouse PWR. The purpose of this work was to provide input to an overall program to evaluate the commercial feasibility of selected nuclear energy systems to support the Department of Energy's Nonproliferation Alternative Systems Assessment Program (NASAP).

The work reported here consisted of two phases. First, a preliminary assessment of alternate improvement concepts was performed to identify those that offered the best potential for near-term uranium savings with minimal plant and fuel modifications, and research, development, and demonstration (RDD) requirements. Then, for each of the selected concepts, a more detailed study was performed to quantify the potential uranium savings and fuel cycle costs, as well as the needed plant/fuel modifications and the RDD requirements, including costs and implementation schedules.

The reference case for this study was a 3411 MWt four-loop PWR, using the standard 12-foot 17 x 17 fuel assembly, with out/in fuel management and an annual refueling interval with a discharge burnup of 33,000 MWD/MTM.

The principal results and conclusions of this study are as follows:

- Increasing discharge burnups (from a reference value of 33,000 MWD/MTM to 45,000 MWD/MTM) with an optimized fuel assembly design offers the best potential for near-term (within the next 20 years) uranium savings. About 12-percent U_3O_8 savings may be attainable here. However, the realities of the marketplace will most probably lead to a very gradual vendor/ utility acceptance and implementation of higher burnups.

Therefore, approximately 10 to 15 years may elapse before these concepts are fully implemented in practically all operating PWR reactors, and the full 12-percent potential U_3O_8 annual savings may not be realized before the 1990s.

- Improved fuel management schemes, such as end of cycle coastdown while maintaining 100% thermal power, low leakage cores, and reinsertion of irradiated fuel assemblies offer combined U_3O_8 savings of about 3 to 4 percent if fully implemented in all PWR reactors. (Although no evaluation of the economically optimum coastdown period was made, with coastdown to 60% power, the combined total U_3O_8 savings would be about 6%).

- Other concepts evaluated by scoping analyses during the preliminary phase of the study, such as radial and axial blankets, a Zircaloy baffle, and a variable lattice design, were judged to offer little likelihood of significantly contributing to the U_3O_8 savings on a near-term basis (within the next 20 years).

It is recommended that DOE continue to encourage the participation of all concerned parties in programs that will lead to the speedy implementation of the cost-effective uranium savings concepts.

SECTION 1

INTRODUCTION AND SUMMARY OF RESULTS

1.1 PURPOSE AND SCOPE

This report contains the results and conclusions of an overall evaluation of various concepts which might be applied to the once-through PWR fuel cycle to improve uranium utilization. This work (identified as NASAP Task 6), will serve as input to an overall program to evaluate the commercial feasibility of selected nuclear energy systems to support the Department of Energy's Nonproliferation Alternative Systems Assessment Program (NASAP). The main objectives of this work were as follows:

- To identify and describe the various uranium saving concepts applicable to the once-through PWR fuel cycle
- To estimate the uranium savings, plant/fuel modifications, and the costs/schedules of implementation associated with each concept
- To select the most promising concepts for detailed evaluation, including uranium and SWU requirements and fuel cycle costs for the first cycle, the equilibrium cycle, and over a 30-year period
- To provide an estimate of the commercialization date for each selected concept, based on a detailed breakdown of the development program needs

1.2 BASES AND ASSUMPTIONS

The reference case for this study was a four-loop PWR (1125 MWe) using the standard Westinghouse 17 x 17 fuel assemblies. Table 1-1 gives the pertinent design details for this reactor.

The following assumptions and design bases were used for each evaluated concept:

- A Cycle 1 length of 435 days. Subsequent cycle lengths were based on either annual or 18-month refueling intervals. In either case, the refueling shutdown length was 45 days.

- An operating capacity factor of 74 percent. This corresponds to an effective capacity factor (including shutdown for refueling) of 65 and 68 percent for the annual and 18-month cycles, respectively.

- Economics data (U_3O_8 and SWU costs, fabrication and shipping costs, and the like) as given in Table 1-2. These data were drawn from the November 30, 1978, NASAP data base. The unit fabrication cost was varied per ORNL suggestions where the reference case is $110/kg U, the high burnup cases are assumed to be $130/Kg U (average of $120-140/kg U in NASAP data base) and the optimized fuel assembly is assumed to have the same cost per assembly as the standard assembly (resulting in $120/kg U and $140/kg U for the OFA at standard and high burnups, respectively.

Table 1-3 lists the concepts that were selected for detailed study, as discussed in section 2.

1.3 SUMMARY OF RESULTS

Table 1-4 summarizes the principal results obtained in this study. The U_3O_8 and SWU requirements for each concept are shown for a 30-year period. The figures for the reference case were normalized to 100 for each entry, so that direct comparisons among the alternate concepts can be made. The bottom line potential U_3O_8 savings of 16 percent include approximately 4 percent savings due to improved fuel management including end of cycle coastdown with power reduction to 60 percent of full rated power. The figures in parentheses are for 18-month cycles. It is clear that the longer cycles are detrimental from the standpoint of uranium utilization;(1) however, if sufficiently improved plant availability can be achieved, the longer cycles would lead to lower system power generation costs. An additional motivation for longer cycles is the potential for lowering personnel exposure to radiation.

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1. The uranium utilization penalty associated with the longer cycles could be reduced significantly by going to much higher discharge burnups (greater than 55 GWD/MTM), and hence more zones in a core. The burnable poison penalty associated with longer cycles, however, will continue to be a major factor in the comparison.

TABLE 1-1

REACTOR DESIGN DATA

THERMAL AND HYDRAULIC DESIGN PARAMETERS

Reactor core heat output (MWt)	3411
System pressure, nominal (psia)	2250
Total thermal flow rate (10^6 lbm/hr)	140.3
Coolant temperature (°F)	
- Nominal inlet	558
- Average in core	589

CORE MECHANICAL DESIGN PARAMETERS

Fuel assemblies	
- Number of fuel assemblies	193
- UO_2 rods per assembly	264
- Rod pitch (in.)	0.496
- Overall dimensions (in.)	8.426 x 8.426
Fuel rods	
- Number	50,952
- Outside diameter (in.)	0.374
- Diametral gap (in.)	0.0065
- Clad thickness (in.)	0.0225
- Clad material	Zircaloy 4
Fuel pellets	
- Density (percent of theoretical)	95
- Diameter (in.)	0.3225
- Length (in.)	0.530
Structure characteristics	
- Core diameter (equivalent) (in.)	132.7
- Core height (active fuel) (in.)	143.7

TABLE 1-1 (cont)

REACTOR DESIGN DATA

CORE MECHANICAL DESIGN PARAMETERS (cont)

Reflector thickness and composition	
- Top - water plus steel (in.)	10
- Bottom - water plus steel (in.)	10
- Side - water plus steel (in.)	15
- H_2O/U molecular ratio core, lattice (cold)	2.41
Feed enrichment (first core) (w/o)	
- Region 1	1.4
- Region 2	2.1
- Region 3	2.9

TABLE 1-2

ECONOMICS DATA BASE

Cost of U_3O_8 (\$/lb)	40.00
Cost of U_3O_8 to UF_6 conversion (\$/kg U)	4.00
Cost of separative work (\$/SWU)	100.00
Tails assay of diffusion plant at time of enrichment (w/o)	0.20
Batch unit fabrication cost (\$/kg U)(a)	110.00 to 140.00
Spent fuel shipping cost (\$/kg m)	15.00
Preoperation carrying charge rate (%/yr)	7.70
Carrying charge rate before and after commercial operation (%/yr)	7.70
Disposal cost (\$/kg m)	120.00
Electrical efficiency ratio (MWe/MWt)	0.33(b)
Discount rate for calculating levelized costs	4.50

(a) Varied per ORNL Suggestion - References 110, High Burnup 130, OFA 120 and OFA at High Burnup 140.

(b) Assuming wet cooling towers

TABLE 1-3

IMPROVEMENT CONCEPTS SELECTED FOR DETAILED STUDY

Concept No.	Refueling Interval (months)	Description
1.0, 1.1	12, 18	Reference case
2.0, 2.1	12, 18	High burnup (45 GWD/MTM)
3.0	12	Optimized fuel assembly (OFA), 36 GWD/MTM
3.1, 3.2	12, 18	OFA, high burnup (45 GWD/MTM)
4.0	12	Combination of 4.1, 4.2, and 4.3
4.1	12	Reference core, end of cycle coastdown
4.2	12	Reference core, low leakage fuel management
4.3	12	Reinsertion of least burned assemblies[a]
5.0, 5.1	12, 18	Lower power density core (241 assemblies, 3800 MWt, 14-foot fuel, 36 GWD/MTM)
6.0	12	Combination of 3.1 and 4.0

a. Regions 1 and 2 fuel only

TABLE 1-4

SUMMARY OF RESULTS - ONCE-THROUGH PWR IMPROVEMENT CONCEPTS

	Concept	Requirements		Levelized Fuel Cycle Costs	RDD Cost[a] ($ x 10^6)	RDD Time[b] (years)
		U_3O_8	SWU			
1.0	Reference[c]	100 (115)[d]	100 (122)	100 (116)	--- ---	--- ---
2.0	High burnup (45 GWD/MTM)	91 (101)	98 (113)	95 (107)	7	8-10
3.0	OFA, 36 GWD/MTM	94	94	95	15	6-8
3.1	OFA, high burnup (45 GWD/MTM)	88 (99)	94 (111)	93 (105)	7	8-10
4.0	Improved fuel management[e] (EOC coastdown, low leakage fuel management, reinsertion of Region 1, 2, assemblies)	94	91	95	---	---
5.0	Lower power density core[f]	97 (108)	98 (114)	100 (112)	6	4-5
6.0	Combination of 3.1 and 4.0	84	89	91	---	---

a. These costs are for a single demonstration program.
b. The time refers to date of commercial offering, not reactor operation.
c. All figures for the reference case have been normalized to 100, for a 30-year period.
d. Figures in parentheses refer to 18-month cycle.
e. Based on EOC-coastdown to 60% power
f. Figures have been normalized to the same energy output over a 30-year period as in reference case.

SECTION 2

CONCEPTS SELECTED FOR DETAILED EVALUATION

2.1 REFERENCE CASE

The reference case for this study was a four-loop PWR (3411 MWt) using the standard Westinghouse 17 x 17 fuel assemblies, with a target discharge burnup of 33 GWD/MTM. Table 1-1 gives the pertinent design details.

Two sets of calculations, for 12- and 18-month refueling intervals, were performed for this core (concepts 1.0 and 1.1 in Table 1-3). Two principal computer codes were used in this study; a modified version of LEOPARD and an instant fuel cycling code. The modified LEOPARD is a point model cell homogenization, neutron spectrum, isotopic depletion program and is the basis for all reactivity calculations, depletion rates and reactivity feedback models. Microscopic cross section data is based on the ENDF/B library with minor modifications. The instant cycling program is used for long range planning and for preliminary cycle lifetime calculations. Using eigenvalues as a function of burnup from the cell depletion, the code calculates cycle lifetimes. In addition it can perform an economic evaluation of the cycling pattern. Table 2-1 gives the U_3O_8 and SWU requirements for the first and equilibrium cycles, plus the 30-year totals for both the 12- and 18-month refueling cases. Note that the 30-year totals do not take credit for the lower discharge burnup of the last two feed regions. In NASAP terminology, these totals are "gross" requirements. Also shown in Table 2-1 are (1) the charge and discharge masses of fissile and fertile materials for the first core and the equilibrium region, and (2) the levelized fuel cycle costs for the 30-year period.

Table 2-1 shows that the 18-month cycle requires significantly more U_3O_8 and SWUs (15 and 22 percent, respectively) than the 12-month cycle, over the 30-year period. In addition, it shows a 16-percent increase in the levelized fuel cycle costs. (Note that no attempt was made to perform any optimization for the 18-month cycle cases; however, the effect of the burnable poison penalty associated with longer cycles tends to become the major factor in the higher valves obtained.)

Despite the above results, there is an increasing tendency among utilities to consideration of longer cycles. Potential benefits of longer cycles include lower system power generation cost and lower personnel exposure to radiation.

2.2 HIGH BURNUP

Higher discharge burnups improve fuel utilization in two ways. The biggest improvement results from being able to increase the number of fuel regions in a core. The second benefit is due to the nonlinear decrease in fuel reactivity with increased burnup because of the buildup of fissile plutonium.

The fuel region discharge burnup (Xd) is related to the core average burnup (X) at end of cycle by the relation

$$\frac{Xd}{\bar{X}} = \frac{2n}{n+1}$$

where n is the number of fuel regions in a core. This relationship shows that increasing the number of fuel regions also increases the ratio Xd/X; the ratio approaches its theoretical limit of 2 as n approaches infinity. For example, for a fixed feed enrichment in an equilibrium cycle, the discharge burnup can be increased by approximately 7 percent by going from three to four fuel regions. In this case, however, the refueling interval is shortened significantly. To maintain an annual or an 18-month refueling interval, the discharge burnup must be increased in integral units of the cycle burnup, or else multibatch feed regions must be used. Thus, for a cycle length of 10,000 MWD/MTM, the discharge burnup must be increased from 30,000 to 40,000 MWD/MTM in going from three to four fuel regions.

Two sets of calculations were performed to determine the U_3O_8 and SWU requirements and the fuel cycle cost associated with the high discharge burnup fuel. The first was for an annual refueling interval, the second for an 18-month refueling interval. In both cases a basic out-in loading pattern was used with appropriate burnable poison penalties incorporated. Table 2-2 summarizes the U_3O_8 and SWU requirements and the relative fuel cycle costs for the two cases. High burnup with annual refueling shows a 9-percent savings in U_3O_8 and 2-percent savings in SWU requirements over a 30-year period, compared to the reference case. The corresponding fuel cycle cost savings, levelized over a 30-year period, are about 5 percent. For the 18-month refueling case at high discharge burnup, an additional 1 percent in U_3O_8 and 13 percent in SWUs are required over the 30-year period. There is a 7-percent fuel cycle cost penalty as well.

A determination of the U_3O_8 savings attainable by employing high burnup fuel with a low leakage loading pattern was beyond the scope of this study. This type of fuel management requires a significant number of burnable poison rods each cycle and determination of U_3O_8 and SWU requirements requires multidimensional depletion calculations over several cycles. It is expected that loading patterns other than the basic out-in might lead to additional U_3O_8 utilization benefits for high burnup cycles beyond those reported herein.

No significant fuel design and plant modifications are anticipated in going to higher burnups. Small changes in plenum lengths, and possibly in the backfill pressures, may be the only fuel design changes needed to accommodate high burnup operation. Some changes in the spent fuel storage racks may be needed to allow for the higher enrichments (3.8 to 4.2 weight percent) associated with high burnup operation, since current licensing requirements are based on criticality of unirradiated fuel, regardless of the burnup level of the stored fuel. Other changes include those to the upper limit of enrichments in the conversion lines of fabrication plants. The costs associated with such changes will be plant dependent, and are not included here.

To demonstrate the feasibility of high discharge burnups, well-characterized PWR fuel assemblies will have to be irradiated to high burnups to quantify the effects of high burnup operation on the fuel assembly mechanical integrity. Furthermore, generic nuclear, thermal/hydraulic, and safety analyses would have to be performed to identify potential design or safety problems at an early stage. Table 2-3 gives the schedule and costs of a single high burnup demonstration program in an operating PWR. Such a program would involve the irradiation of two to four test assemblies for a fourth and a fifth cycle of operation, and the associated onsite and post irradiation fuel examinations. It should be noted that eight test assemblies should be available to ensure that two to four fuel assemblies would operate to the high discharge burnup, allowing the option to destructively examine some assemblies after cycles 3 and 4.

Currently, the first three items in Table 2-3 have been completed in two separate programs to demonstrate high discharge burnups in Westinghouse PWRs. Thus, under current schedules, higher burnup fuel (greater than 33,000 MWD/MTM) may be offered in the early 1980s. However, fuel intended for discharge burnups of approximately 45,000 MWD/MTM may not be offered before the late 1980s, and it will be a few years later before entire fuel regions are operated to these high burnups. It is expected that utility acceptance of high burnup fuel will be very gradual, and that high burnup fuel management schemes on a routine basis will not occur before the early 1990s. Table 2-4 shows an estimate of the adoption rate of high burnup fuel versus time.

2.3 OPTIMIZED FUEL ASSEMBLY

The Westinghouse 17 x 17 optimized fuel assembly (OFA) differs mechanically from the standard 17 x 17 assembly in two basic ways: it has a higher water/fuel ratio, and it uses Zircaloy instead of Inconel grids (except for the top and bottom grids). Table 2-5 gives the pertinent design information for this assembly.(1)

Because of the smaller fuel rod diameter, and thus less uranium loaded per assembly, a higher discharge burnup (36,000 MWD/MTM) is required in the OFA to match the total energy output of a standard fuel assembly discharge at 33,000 MWD/MTM. However, the improved neutron economy in the OFA results in net U_3O[illegible] SWU savings over the standard assembly, for equivalent energy output.

Table 2-6 summarizes the calculated U_3O_8 and SWU requirements and the levelized fuel cycle costs (relative) for the three OFA cases considered (concepts 3.0, 3.1 and 3.2 in Table 1-3). The 12-month cycle with 36,000 MWD/MTM discharge burnup shows approximately 6-percent savings in both U_3O_8 and SWU requirements over the reference case. The corresponding fuel cycle costs are 5 percent lower. The largest savings, however, are obtained at the high burnups. Here, for a 12-month cycle, the OFA provides 12, 6, and 7 percent savings in U_3O_8, SWUs, and fuel cycle costs, respectively. Because of the higher enrichments required at these high burnups, the SWU savings are lower by a factor of two than the U_3O_8 savings.

The fuel assembly modifications in the Westinghouse OFA include a smaller-diameter fuel rod, and the use of Zircaloy, instead of Inconel, grids. No plant modifications are anticipated in retrofitting the OFA into existing plants.

The RDD efforts needed to demonstrate the adequacy of the Westinghouse OFA design include first-time engineering costs and an in-core demonstration program. In particular, the compatibility of the OFA with the standard 17 x 17 fuel assembly would have to be demonstrated for plants that would use the OFA after initial operation with the standard assemblies. Table 2-7 gives the schedule and cost of developing an OFA. An RDD program similar to that shown in Table 2-7 would be needed for each type of optimized fuel assembly (e.g., 14 x 14 and 15 x 15).

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1. For more detail, see WCAP-9500, "Reference Core Report, 17 x 17 Optimized Fuel Assembly."

Current Westinghouse plans call for a demonstration program involving the OFA by the end of 1979 or early 1980 (item 5 in Table 2-7 for the 17 x 17 OFA). The first Westinghouse PWR to employ the 17 x 17 OFA is scheduled for operation by 1982. It is expected that most Westinghouse PWRs will employ optimized fuel assemblies of one type or another by the early 1990s. The transition to an OFA with 45,000 MWD/MTM discharge burnup will not occur before the early 1990s for most plants.

2.4 IMPROVED FUEL MANAGEMENT

Improved fuel management concepts, described in the following paragraphs, involve mainly analytical efforts. Fuel/plant modifications would not be required.

2.4.1 End of Cycle Coastdown

An end of cycle (EOC) coastdown has been routinely practiced by many utilities. Schedular considerations seem to be the main factors in its use. Coastdown operation can be effected in two ways: by reducing the average coolant temperature while operating at 100 percent of rated thermal power, or by reducing both coolant temperature and reactor power. The first cycle in which coastdown operation is used can generate up to 10 percent additional energy. However, this reduces the energy output capabilities of subsequent cycles. The calculations performed here were based on full-power operation until the last 70 days of operation, when the core thermal power is gradually reduced to 60 percent of full rated value, at the end of cycle. (No assessment was done to determine the economically optimum coastdown period.) The net effect is an operating capacity factor of 72 percent, instead of the 74 percent used in the reference case. This coastdown is performed during every cycle, and is thus preplanned. Table 2-8 gives the results for this calculation. The indicated U_3O_8, SWU, and fuel cycle costs savings of 7, 10, and 4 percent, respectively, are somewhat misleading because they do not reflect the total effect on overall system power generation cost. The optimum coastdown period for minimizing total power generation cost is a function of U_3O_8 and SWU price and replacement power cost. Most utilities have not normally scheduled coastdown operation on a routine basis.

For the case of end of cycle operation at 100-percent thermal power, but with reduced coolant temperature (5^oF to 10^oF reduction), the associated U_3O_8 savings would be 0.5 to 1.0 percent relative to the reference case.

2.4.2 Low Leakage Fuel Management

In a three-region, out/in fuel management, the feed region is loaded at or near the core periphery, where the probability of neutron leakage is highest. The neutron leakage can be significantly reduced by placing relatively less-reactive burned fuel at the core periphery. The degree to which this can be accomplished depends on other design constraints, mainly on peaking factors and the burnable poison requirements. The benefit of low leakage fuel management is naturally greatest for cores that have inherently large radial leakage, that is, two-loop plants. For these plants, 3- to 4-percent uranium savings are attainable in an equilibrium cycle by this fuel management technique. However, for four-loop plants the potential savings are somewhat smaller.

The calculations performed show that over a 30-year period, 1-percent savings in U_3O_8 and 2-percent in SWUs may be attainable using low leakage fuel managements. The corresponding fuel cycle cost saving, however, is only 1 percent. Table 2-8 summarizes the calculated results.

2.4.3 Reinsertion of Discharged Assemblies

Because of the nonuniform burnup of the Region 1 and 2 assemblies, those with the lowest burnup can be reinserted and driven for an additional cycle of operation. Uranium savings result from the increased burnup of a portion of the discharged region.

The calculations performed here show that over a 30-year period, 1-percent U_3O_8 and SWU savings may be realized using this scheme. About 1-percent savings in fuel cycle costs might be realized. Table 2-8 summarizes the calculated results.

2.5 LOWER POWER DENSITY CORE

A lower power density core, using 241 14-foot 17 x 17 fuel assemblies and rated at 3800 MWt, would operate with significantly increased margins to safety limits. This concept, which would require major reactor changes, is not retrofit table. Table 2-9 gives the pertinent design details for this concept. The calculations performed cover both 12-month and 18-month cycles. Table 2-10 shows the U_3O_8 and SWU requirements plus the relative fuel cycle costs associated with the two refueling intervals. For the 12-month cycle, this concept shows 3-percent U_3O_8 savings and about 2-percent SWU savings over a 30-year period. However, for the particular set of economic conditions and design parameters used for this analysis, the levelized fuel cycle cost (relative) is approximately the same as that of the reference case. (It should be noted that the energy output of this plant is considerably larger than that of the reference case; the fuel cost comparison on an equal energy output basis would show lower costs for the lower power density core.)

The lower power density core would require changes in plant design, such as larger pressure vessel and containment structure, modified plant internals, and changes in the new and spent fuel storage racks and perhaps in the fuel handling equipment. Table 2-11 gives the RDD program costs and schedules for this concept. The costs are really first-time engineering costs; there are relatively few feasibility questions to be answered, if any. These costs, approximately $6 million (1979), are incremental costs relative to the reference case.

The potential for market acceptance depends on the impact of plant capital costs due to the design changes associated with the low power density core concept. The significant improvements in margins to safety limits and the fact that no new technology is involved are expected to improve the potential for market acceptance.

TABLE 2-1

REFERENCE CASE U_3O_8 AND SWU REQUIREMENTS, FISSILE/FERTILE MATERIAL LOADING/DISCHARGE, AND FUEL CYCLE COSTS

Parameter	First Core	Equilibrium Region 12-Month Cycle	Equilibrium Region 18-Month Cycle
Feed enrichment (w/o)	1.4, 2.1, 2.9	3.05	3.5
Number of assemblies	65, 64, 64	53	83
Discharge burnup (GWD/MTM)		33	33
Cycle length (MWD/MTM)	12,350	9,070	14.240
Effective capacity factor (%)	67	65	68
Loading (MTU)	89.1	24.5	38.3
Fissile discharge U, Pu (MT)	0.58, 0.52	0.18, 0.16	0.39, 0.26
Fertile discharge U, Pu (MT)	85.5, 0.19	23.4, 0.07	36.2, 0.10
U_3O_8 (ST)(a)(b)	500	181	330
U_3O_8 (ST/GWDe)	0.714	0.679	0.788
30-year total U_3O_8(b) (ST)		5,466	6,294
SWUs (x 10^3)(b)	269	110	212
SWUs (x 10^3/GWDe)	0.358	0.412	0.506
30-year total SWUs(b) (x 10^3)		3,275	3,992
Levelized fuel cycle costs (¢/MBtu)		53.2	61.6

a. ST = short tons

b. 1125 MWE

TABLE 2-2

HIGH BURNUP CONCEPT - U_3O_8 AND SWU REQUIREMENTS AND FUEL CYCLE COSTS

Parameter	12-Month Cycle	18-Month Cycle
Feed enrichment (w/o)	3.75	4.17
Number of assemblies	39	61
Discharge burnup (GWD/MTM)	45	45
Loading (MTU)	18.0	28.2
Effective Capacity Factor (%)	65	68
U_3O_8 (ST)(a)	165	290
U_3O_8 (ST/GWDe)	0.621	0.694
30-year total U_3O_8(a) (ST)	4,956	5,510
SWUs (x 10^3)(a)	109	198
SWUs (x 10^3/GWDe)	0.409	0.473
30-year total SWUs(a) (x 10^3)	3,195	3,696
Levelized fuel cycle costs (relative to reference case)	95	107

a. 1125 MWE

TABLE 2-3

HIGH BURNUP DEMONSTRATION PROGRAM

	Item	Time (yr)	Cost ($ x 10^6)
1.	Fabricate and characterize eight demonstration assemblies.	0 to 1	0.5
2.	Irradiate demonstration fuel assemblies for three cycles of reactor operation.	1 to 5	0.5
3.	Perform nuclear and safety analyses for the fourth cycle of irradiation; resolve all licensing concerns including possible technical specification changes.	4 to 5	0.5
4.	Examine fuel after three cycles of operation (channel closure, dimensional changes, clad integrity, etc.).	5 to 5.5	0.5
5.	Same as item 3, but for fifth cycle of irradiation	5 to 6	0.5
6.	Same as item 4, but at end of Cycle 4	6 to 6.5	0.5
	6a. Commercial offering of higher burnups (36K to 38K)		
7.	Irradiate demonstration assemblies for fifth cycle of operation.	6 to 7	--
8.	Perform onsite and offsite fuel examinations on selected fuel rods and pellets.	7 to 7.5	1.0
9.	Recommend fuel/assembly design changes, if any, to allow for high burnup operation.	7.5 to 8	1.0
10	Generic licensing of high burnup fuel		2.0
11	Commercial offering of high burnup fuel regions (45 GWD/MTM)	8 to 10	--
12	Fabricate first full region for higher discharge burnup (45 GWD/MTM).	10 to 15	--
	TOTAL	10 to 15	7.0

TABLE 2-4

ESTIMATED IMPLEMENTATION RATE OF HIGH BURNUP FUEL REGIONS IN OPERATING REACTORS

Year	% of Reactors Using High Burnup Fuel[a]
1980	0
1985	10
1990	60
1995	95

a. Discharge burnup of 45 GWD/MTM

TABLE 2-5

WESTINGHOUSE OPTIMIZED FUEL ASSEMBLY DESIGN INFORMATION

Parameter	Standard 17 x 17 Assembly	Optimized 17 x 17 Assembly
Relative moderating ratio	1.0	1.2
Fuel rod diameter (in.)	0.374	0.360
Clad thickness (in.)	0.022	0.022
Fuel pellet diameter (in.)	0.322	0.309
Grids per fuel assembly	8	8
Grid material	Inconel-718	6 Zircaloy-4 2 Inconel 718 (top and bottom)

TABLE 2-6

WESTINGHOUSE OPTIMIZED FUEL ASSEMBLY CONCEPT - U_3O_8 AND SWU REQUIREMENTS AND FUEL CYCLE COSTS

Parameter	12-Month Cycle		18-Month Cycle
Discharge burnup (GWD/MTM)	36	45	45
Feed enrichment (w/o)	3.11	3.66	4.07
Number of assemblies	53	42	67
Loading (MTU)	22.4	17.8	28.4
Effective Capacity Factor (%)	65	65	68
U_3O_8 (ST)(a)	170	160	285
U_3O_8 (ST/GWDe)	0.636	0.598	0.682
30-year total U_3O_8(a) (ST)	5,118	4,800	5,437
SWUs (x 10^3)(a)	104	104	193
SWUs (x 10^3/GWDe)	0.388	0.391	0.461
30-year total SWUs(a) (x 10^3)	3,086	3,080	3,627
Levelized fuel cycle costs (relative to reference case)	95	93	105

a. 1125 MWE

TABLE 2-7

OPTIMIZED FUEL ASSEMBLY DEVELOPMENT COSTS AND SCHEDULES

Item	Activity	Time (yr)	Cost ($ x 10^6)
1. Develop fuel assembly design concept; investigate potential materials.	FTE[a]	0	1
2. Develop material fabrication techniques; construct development prototypes of competing designs; initiate preliminary safety analysis.	FTE	1	1
3. Test (mechanical/hydraulic) prototypes of competing designs; order manufacturing equipment for design prototype; continue preliminary safety analysis.	FTE	2	2
4. Fabricate design prototype; perform flow and mechanical tests; initiate FSAR-level safety analysis.	Testing	3	3
5. Fabricate prototype demonstration assemblies; insert in core; continue FSAR-level safety analysis.	Testing	4	2
6. Inspect first cycle of demonstration fuel assembly operation; order production dies and fabrication tooling; complete safety analysis; submit licensing documents.	Demonstration and production	5	3
7. Inspect second cycle of demonstration fuel assembly operation; install and check out fabrication tooling.	Demonstration and production	6	2

a. FTE = first-time engineering

TABLE 2-7 (cont)

OPTIMIZED FUEL ASSEMBLY DEVELOPMENT COSTS AND SCHEDULES

Item	Activity	Time (yr)	Cost ($ x 10^6)
8. Inspect third cycle of demonstration fuel assembly operation; fabricate full-region fuel assemblies.	Demonstration and production	7	1
9. Ship fuel region(s).		8	-
		TOTAL	15

a. FTE = first-time engineering

TABLE 2-8

IMPROVED FUEL MANAGEMENT CONCEPTS - U_3O_8 AND SWU REQUIREMENTS AND FUEL CYCLE COSTS

Parameter	EOC Coastdown[a]	Low Leakage Fuel Management	Reinsertion of Assemblies
Feed enrichment (w/o)	2.88	2.99	3.05
Number of assemblies	52	53	53
Refueling interval (months)	12	12	12
Operating capacity factor (%)	72	74	74
Effective Capacity Factor (%)	63	65	65
Discharge burnup (GWD/MTM)	33	33	33
Loading (MTU)	24.0	24.5	24.5
U_3O_8 (ST)[b]	167	177	181
U_3O_8 (ST/GWDe)	0.644	0.664	0.674
30-year total U_3O_8[b] (ST)	5,065	5,392	5,392
SWUs ($\times 10^3$)[b]	99	107	110
SWUs ($\times 10^3$/GWDe)	0.379	0.400	0.409
30-year total SWUs[b] ($\times 10^3$)	2,962	3,210	3,258
Levelized fuel cycle costs (relative to reference case)	96	99	99

a. Coastdown to 60% of full rated core thermal power for each cycle

b. 1125 MWE

TABLE 2-9

LOWER POWER DENSITY CORE DESIGN DETAILS

Parameter	Low Power Density Core	Reference Case
Reactor core heat output (MWt)	3800	3411
System pressure, nominal (psia)	2250	2250
Number of fuel assemblies (17 x 17)	241	193
Core height, active fuel (ft)	14	12
Reactor vessel ID (in.)	188	173
Containment volume (relative)	1.07	1.0
Specific power (MWT/MTU)	29	38
First core enrichments		
Region 1	1.5	1.4
Region 2	2.3	2.1
Region 3	2.9	2.9

TABLE 2-10

LOWER POWER DENSITY CORE CONCEPT - U_3O_8 AND SWU REQUIREMENTS AND FUEL CYCLE COSTS

	12-Month Cycle	18-Month Cycle
Feed enrichment (w/o)	3.18	3.56
Number of assemblies	47	73
Discharge burnup (GWD/MTM)	36	36
Loading (MTU)	25.2	39.1
U_3O_8 (ST)$^{(b)}$	195	341
U_3O_8 (ST/GWDe)	0.656	0.730
30-year total $U_3O_8{}^{(a)}$ (ST)	5,921$^{(b)}$ (5,250)$^{(a)}$)	6,578$^{(b)}$ (5,905)$^{(a)}$
SWUs ($\times 10^3$)$^{(b)}$	120	220
SWUs ($\times 10^3$/GWDe)	0.404	0.472
30-year total SWUs$^{(a)}$ ($\times 10^3$)	3,584$^{(b)}$ (3,217)$^{(a)}$	4,153$^{(b)}$ (3,728)$^{(a)}$
Levelized fuel cycle costs (relative to reference case)	100	112

(a) Normalized to 3411 MWt

(b) 1254 MWE

TABLE 2-11

LOWER POWER DENSITY CORE DEVELOPMENT COSTS AND SCHEDULES

	Item	Time (yr)	Cost[a] ($ x 10^6)
1.	Reactor internals design and analysis	0-2	0.5
2.	Scale-model internals tests	1-3	2.0
3.	Reactor vessel design and analysis	1-2	0.5
4.	Nuclear and thermal/hydraulic analyses	0-2	1.0
5.	Generic PSAR preparation	2-4	2.0
6.	Commercial offering	4-5	--
7.	Authority to proceed (from utility)	5-6	--
8.	Construction period	5-15	--
9.	Commercial operation	15	--
	TOTAL	15	6.0

(a) Figures shown are incremental costs over and above those associated with the reference core.

SECTION 3

OTHER CONCEPTS EVALUATED

3.1 GENERAL

Concepts which were evaluated only during the preliminary phase of this study are discussed in this section. These concepts were not selected for further study because of one or more of the following reasons:

- Low potential U_3O_8 savings
- High associated economic penalties
- Long lead times to implementation

Table 3-1 summarizes the preliminary evaluation results for these concepts.

3.2 BETTER REFLECTOR

Current design PWRs use a stainless steel baffle (or shroud) around the core periphery. Analyses show that improved neutron economy, in the form of lower radial leakage, could be obtained if Zircaloy were to replace the stainless steel in the baffle. Uranium savings of 1 to 2 percent might be realized, depending on the plant design (two-loop versus four-loop) and on the fuel management employed (low leakage versus standard out/in).

Minimum fuel modifications would be required to accommodate a Zircaloy baffle in new model plants. However, retrofitting the Zircaloy baffle to existing plants would entail significant difficulties. The cost of such retrofitting is difficult to estimate. On a one-time basis, it could run into the tens and perhaps hundreds of millions of dollars, when replacement power costs are factored in. Even for new plants, a considerable RDD effort, in the area of \$5 to \$10 million, would be needed to determine the feasibility and potential problems associated with the behavior of a Zircaloy baffle under high long-term neutron irradiation.

For new plants, a Zircaloy baffle could be employed within 10 to 15 years of RDD initiation. The likelihood of resolving the material concerns is fairly good, since high burnup experience with Zircaloy clad fuel is already available; that could serve as a useful base for further data acquisition.

3.3 VARIABLE LATTICE DESIGN - LOOSE LATTICE

In a recycle fuel economy, the buildup of fissile plutonium isotopes is an important consideration in choosing the appropriate lattice water/fuel ratio. The optimum lattice for a recycle mode of operation, therefore, has a relatively low water/fuel ratio to maximize the conversion of U-238 to Pu-239 within economic and operating constraints. In a once-through fuel cycle, a wetter lattice would improve fuel utilization. Thus, for fuel having a very dry lattice, improved fuel utilization is possible by going to a wetter lattice. One way in which this can be accomplished is by removing a select number of burned fuel rods from each assembly in a given fuel region, thereby increasing the installed reactivity of the fuel. The resultant assembly has a higher effective lattice pitch, hence the term loose lattice. The fuel rod removal might be done during the refueling period. The exact number and location of the rods to be removed is a function of the degree to which the assembly is undermoderated, the available margins to the core design and operating limits (kw/ft, peaking factors, DNBR, and the like), and the assembly design.

It is estimated that for current design PWRs, 3- to 5-percent improvement in fuel utilization might be achieved by the loose lattice concept (and reuse of all the rods removed from assemblies). However, operating constraints may severely limit the practicality of this concept. The removal of fuel rods from an assembly which was not specifically designed to allow for this possibility would create severe practical problems, especially under tight refueling schedules.

Considerable plant modifications, mainly in the refueling equipment, would be required to implement this concept. The assembly design would need to be changed, preferrably to a removable rod type.

The RDD effort associated with this concept is estimated at $10 to $20 million. This effort would include a demonstration program to prove the feasibility of reconstituting fuel assemblies during a refueling shutdown.

The concept could be implemented in 7 to 10 years from the time an RDD program is initiated. The probability of technical success is moderate. A similar operation was performed for Saxton Core III,(1) an experimental mixed oxide reactor with a fuel that was 3 feet long, versus the 12-foot fuel used in current PWRs.

3.4 RADIAL AND AXIAL BLANKETS

Scoping studies have shown that the use of radial blankets in PWRs can result in combined uranium savings of 1 to 2 percent, depending on the manner in which this concept is implemented. The benefit results from replacing enriched fuel with natural or depleted uranium in core locations of low neutron importance, such as the core periphery and core top and bottom segments. The main drawback of this concept is that a smaller portion of the core must now produce a larger portion of the core power. This effectively raises the core specific power, which may violate design and/or operating limits. Furthermore, similar results can be achieved by different means. For example, radial blankets are used to lower the neutron leakage. Low leakage fuel management can achieve the same objective, using fuel that has a higher power capability than does a natural uranium assembly.

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1. Roll, J., "Saxton Plutonium Program, Semiannual Progress Report for the Period Ending December 1968," WCAP-3385-18, May 1969, and Smalley, W. R., "Saxton Plutonium Program, Semiannual Progress Report for the Period Ending June 1969," WCAP-3385-20, October 1969.

The estimated RDD requirements for these concepts can vary from $1 million to $10 million. The upper value would include the case of changes in core size and internals to accommodate both radial and axial blankets. The lower estimate is for the case of loading natural uranium at the top and bottom 6 inches of the fuel rods without changing the overall fuel stack height, and absorbing the resultant penalty on axial peaking factors. The time needed to implement these concepts would be between 2 and 6 years.

3.5 RAPID REFUELING

Two concepts of rapid refueling were evaluated. The first (standard) involves a cold shutdown and would take from 12 to 14 days. Although no conceptual design study was undertaken, it is believed that the second (advanced), to be performed in a hot shutdown condition by means of a redesigned vessel, internals, and the like, would take from 5 to 7 days. The standard rapid refueling corresponds to 6-month cycles, the advanced to 3-month cycles. The uranium savings for these concepts would be 8 to 11 percent and 15 to 18 percent, respectively.

Both concepts would require significant plant modifications. These include changes in the reactor pressure vessels, the containment, and the reactor internals. The RDD costs associated with each concept are given in Table 3-1. Neither concept can be backfitted into existing plants.

TABLE 3-1

SUMMARY OF RESULTS - CONCEPTS EVALUATED DURING PRELIMINARY PHASE ONLY

		RDD	
Concept	Uranium Savings (%)	Cost ($ x 10^6)	Time[a] (years)
Better reflector (Zircaloy baffle)	1 to 2	5 to 10	10 to 15
Variable lattice design - loose lattice	3 to 5	10 to 20	7 to 10
Radial/axial blankets	1 to 2	1 to 10	2 to 6
Rapid refueling			
o Standard	8 to 11	10 to 20	5 to 10
o Advanced	15 to 18	>100	15 to 20

(a) Time to commercial offering

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

Based on the results reported here, the following conclusions may be drawn:

- High burnup with an optimized fuel assembly and improved fuel management schemes offers the best near-term improvement in uranium utilization, with potential savings of about 16 percent. (High burnup with an optimized fuel assembly offers aabout 10 percent.) However, implementation of high burnup fuel regions in operating reactors is expected to be a cautious process. For this reason, the full uranium savings are not expected to have significant impact until the 1990s.

- Further work on the low power density core would be justified if the capital cost penalty associated with a plant employing this concept is sufficiently small such that the U_3O_8 and SWU savings result in lower power generations costs. The increased margins to safety limits provide additional benefits which make this concept very attractive in the current regulatory and licensing climate.

- Other concepts evaluated do not appear to justify further work at this time because of either very long lead time to implementation or the need for expensive RDD programs that would entail essentially new reactor models.

It is recommended that DOE continue to encourage the participation of all concerned parties in programs that will lead to the speedy implementation of the cost-effective uranium savings concepts.