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UC 20d

PRELIMINARY STUDY OF THE
ECONOMICS OF ENRICHING PWR FUEL
WITH A FUSION HYBRID REACTOR

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PRELIMINARY STUDY OF THE
ECONOMICS OF ENRICHING PWR FUEL
WITH A FUSION HYBRID REACTOR

ABSTRACT

This study is a comparison of the economics of enriching uranium oxide for pressurized water reactor (PWR) power plant fuel using a fusion hybrid reactor versus the present isotopic enrichment process. The conclusion is that privately owned hybrid fusion reactors, which simultaneously produce electrical power and enrich fuel, are competitive with the gaseous diffusion enrichment process if spent PWR fuel rods are reenriched without refabrication. Analysis of irradiation damage effects should be performed to determine if the fuel rod cladding can withstand the additional irradiation in the hybrid and second PWR power cycle. The cost competitiveness shown by this initial study clearly justifies further investigations.

1.0 INTRODUCTION

This study is a preliminary comparison of the economics of enriching uranium oxide for Pressurized Water Reactor power plants using the present gaseous diffusion process versus using a fusion hybrid reactor which simultaneously produces electrical power and enriches fuel. Therefore, the simplest fueling scenario which couples the hybrid to present PWR fuel cycle technology is employed. This scenario is defined as the direct cycle in which all reprocessing of PWR fuel is avoided. While the direct cycle avoids reprocessing costs, it penalizes neutronic performance by constraining the fuel form in the hybrid blanket to PWR fuel rods and by precluding the removal of fission products after irradiation in the hybrid. Thus, the criterion established at the outset of the study was that comparable fuel cycle costs from direct cycle scenarios would represent a clear incentive for further analysis of potentially more favorable approaches to fissile fuel production in the hybrid.

The three methods of enriching the fuel in the fusion hybrid reactor which are evaluated are all direct fuel cycles because no mechanical or chemical reprocessing of the uranium oxide fuel pellets is employed. The first method is to irradiate spent fuel rods from PWR assemblies in the fusion hybrid reactor blanket. This method is referred to as the refresh fuel cycle. The second method is to irradiate new fuel rods made with uranium tails and the third method is to irradiate new fuel rods made with natural uranium. For all three cases studied, the fuel rods are rebundled after hybrid enrichment and used to refuel a PWR on its standard fuel cycle (1/3 of the core replaced per year). Sufficient hybrid enrichment was provided to give the fissile content needed for a typical burnup (33 GWd/THM energy production rate) in the PWR.

The results reported here are preliminary in nature and were obtained by a cooperative effort between Westinghouse Divisions. The Nuclear Fuel Division (NFD) Design Group provided Fusion Power Systems (FPS) with the required enrichments for the PWR fuel based on the isotopic compositions of the fuel irradiated in the hybrid as calculated by WFPS. Several iterations were required between the hybrid blanket and PWR core calculations before obtaining the final results. The isotopic composition of the spent fuel for the refresh cycle was also provided by WNFD. Other neutronic calculations associated with the hybrid determined the time required to reach the desired enrichment as a function of the tokamak operation, some aspects of the fuel management, the burnup of the fuel, fluences, and the k_{eff} of the blanket. The fuel cycle costs were determined by WFPS, but with guidance from the Water Reactors Division Marketing-Fuel Application Group so as to be consistent with current utility costing methods and rates. Results have been expressed in cost per kilogram of heavy metal (uranium and plutonium fissile fuel) so that easy comparisons may be made between the fuel production options.

A number of important issues were not considered in any depth during this study including radiation damage, mechanical design, tritium breeding of the hybrid fusion fuel, uniformity of enrichment and proliferation issues. The summary of the results and conclusions of the study are presented in Section 2. The hybrid concept used for this study is defined in Section 3. The nuclear analyses are presented in Section 4. Economics are discussed in Section 5.

2.0 SUMMARY AND CONCLUSIONS

The objective of this preliminary study was to develop scoping estimates of hybrid enrichment economics. Even though preliminary, the multitude of key parameters and assumptions have made the study rather complex. A number of potentially interesting direct fuel cycle variations have been identified. Two basic alternatives which provide maximum coupling between the fusion hybrid reactor and conventional PWR's, yet represent simple, nearer-term applications, were focused on. These alternatives were hybrid reenrichment ("refresh") of spent PWR fuel rods, and hybrid enrichment of new fertile (natural U or tails) fuel rods for direct use in a subsequent PWR burn cycle. The results are based on estimated parameters used in the economic evaluation and normalized to a 1978 startup for both the hybrid plant and the reference nuclear plant. All of the cases studied including the conventional PWR reference assumed a "throw-away" fuel cycle for the spent PWR rods after a 33 GWd/THM burnup in the PWR.

Hybrid irradiation of spent PWR fuel rods in the "refresh" concept resulted in ~ 50% lower PWR fuel cycle costs and ~ 20% lower PWR power generation costs than those for the conventional PWR enrichment scenario. Hybrid irradiation of new fuel rods manufactured from tails or natural uranium would increase PWR fuel cycle costs by ~ 25% to 50% and power generation costs by ~ 9% to 18% above the reference PWR costs. A reasonable range of parameter variations were considered and the sensitivities developed which showed the hybrid cost scenario varied from competitive to non-competitive compared to the conventional enrichment cost scenario. Thus, the PWR busbar costs of electricity using fuel enriched by the hybrid are projected to bracket busbar costs using conventional nuclear fuel.

The fact that these results indicate comparable PWR busbar costs using hybrid enriched fuel is encouraging since the following aspects of this study are generally unfavorable to the hybrid option:

- The hybrid blanket lattice is comprised of UO_2 fuel rods designed for PWR operation. More favorable hybrid enrichment performance can be obtained using blanket fuel elements designed specifically for the hybrid (e.g., metal alloys, UC, U_3Si , etc.). Some degree of reprocessing of hybrid blanket fuel elements would be required, of course, with such an approach.
- The buildup of fission products represents a significant penalty to the hybrid enrichment scenarios since appreciably more fissile material (1.8% for the refresh case, 0.7% for hybrid irradiation of new fuel rods) is required with spent PWR fuel rods. Here again, some degree of reprocessing would be required to avoid this penalty.
- Private, rather than public, financing of the hybrid was assumed. The comparison is unfair to the hybrid in this regard since enrichment costs for the conventional PWR fuel cycle are based on publicly financed isotopic enrichment facilities.

It should be noted that the combined PWR-Hybrid-PWR burnup would be nearly three times the normal 33 GWd/T PWR cycle and the fluence seen by the fuel rod is estimated to be an order of magnitude larger than present PWR exposures. This prompts concern regarding fuel rod integrity and will require an in-depth technical study (beyond the scope of this initial effort) to verify the fuel rod adequacy.

Assumptions

There are some significant aspects of the basis for hybrid performance and cost information which should be noted in reviewing the results of this report. These aspects are as follows:

Cost and performance data for a hybrid suited for fuel production on a commercial basis have been estimated by extrapolation from Westinghouse work on initial "demonstration" systems: the EPRI-sponsored TCT hybrid⁽¹⁾ and the DoE Demonstration Tokamak Hybrid Reactor (DTHR)⁽²⁾. The economy of size for the hybrid system was examined using a self-consistent tokamak systems computer code (the COAST code)⁽³⁾. The range of scale-up examined (DTHR to ~ 33% larger size than DTHR) was used to establish the formula for capital cost adjustments and performance changes. The U tails fuel case was used for the data base input. Over this entire range, a "near-ignition" plasma was used to establish a conservative basis for hybrid circulating power requirements. Extensive work was not done to determine an economically optimized hybrid reactor plant design.

For these initial estimates, it has been assumed that the reference hybrid is self-sufficient in tritium production. Actually, the breeding ratio is ~ 0.8. The remainder of the tritium must be made by either producing it in the PWR's⁽²⁾ by using double clad Zircaloy pins filled with natural LiF for shim control, purchasing it from a government facility, producing it in the hybrid at the expense of reducing the amount of fissile fuel produced, or by a combination of these methods.

Credit has been taken for the sale of net electricity produced by the hybrid using a sales price based on new 1978 nuclear plant busbar costs (levelized over the plant's 30-year life) for conventional electrical generation. The economic analysis is also based on both the PWR and hybrid plants becoming operational in 1978, with operational lifetimes of 30 years. Fuel related costs are assumed to escalate at a 6% annual rate, and are evaluated as 30-year levelized fuel cycle costs over the plant's lifetime as would be done by the utility economists.

Hybrid enrichment costs have been developed for public (i.e., Government) and private financing. The assumption of public financing gives a considerably more favorable economic picture for the hybrid than private financing and it would be consistent with the financing approach being considered for new isotopic enrichment facilities such as those at Portsmouth, Ohio. This study conservatively assumed present day (early 1978) isotopic enrichment charges to determine the reference PWR fuel cycle cost, rather than increased SWU costs that might be expected following startup of the Portsmouth Plant.

The principal PWR/hybrid fuel cycle considered is the U-Pu cycle with several variations of the direct fuel cycle. The use of U-Pu in the hybrid creates a significant amount of thermal energy for electrical power production, considerably offsetting hybrid plant costs. However, the rationale for choosing U-Pu (as opposed to Thorium/U-233) was not the production of electricity but rather the near-term advantage in utilizing current fuel technology to the greatest possible extent. The direct fuel cycle (same clad and fuel pellets used in PWR and Hybrid) was selected since it represented the simplest case to analyze.

The irradiation time in the hybrid was selected in an attempt to provide "refreshed" or new fuel rods capable of ~ 33 GWd/THM to be consistent with the conventional PWR energy production. The consequence of this approach is significant fuel carrying charges and enrichment costs due to the long irradiation period required to achieve higher enrichments to offset the impurity buildup in the fuel. Fuel carrying charges had to be considered during hybrid enrichment because the fuel will be increasing in value at a significant rate. The "throw-away" fuel cycle was assumed, i.e., no mechanical or chemical reprocessing was used, and no cost credit was allowed for U or Pu fissile fuel in the spent rods. Venting of gas pressure built up in the rods during the first PWR burn was assumed for the spent rod "refresh" case.

Results

It was considered unrealistic to select a single base case for hybrid cost projections due to the many uncertainties in key assumptions. Therefore, various cases were identified to test the effects of the following alternatives:

- PWR fuel rods using natural uranium or tails which are fabricated prior to irradiation in the hybrid versus irradiation of spent PWR fuel rods to "re-enrich" the material. These three cases are compared to the present (reference) PWR fuel cycle (see Figure 2-1). Figures 2-2 through 2-4 define the three hybrid/PWR fuel rod scenarios.
- Public ownership of the hybrid (i.e., no interest during construction and 10% fixed charge rate) similar to present isotopic enrichment facilities vs. private ownership (i.e., 8% interest during construction and 18% fixed charge rate).

Results of these representative hybrid cases were compared to the conventional fuel cycle cost for PWR fuel. The hybrid enrichment economics from the perspective of the resulting PWR busbar cost for the three cases studies are compared to the present (plant on-line in 1978) PWR fuel cycle, power generation cost breakdown in Table 2-1. The hybrid cases shown in this table are based on a DTHR size (5.2 major radius), ignited plasma reactor. The results in Table 2-1 represent a set of parameters which incorporate conservatism by not using a more optimized hybrid size and not assuming public ownership (such as the Portsmouth gaseous diffusion plant or a TVA project). The results show that busbar costs of electricity using fuel enriched in the hybrid bracket the busbar costs for conventional fuel sources depending on the specific parameters, over their range of probable variation, used in the economic analysis. More specific comments on these results follow:

- The irradiation time in the hybrid varied from ~ 9 to ~ 11 years to reach enrichments of 3.9 to 5.0 w/o fissile material using a relatively conservative 2 MW m^{-2} fusion neutron wall loading concept.

Figure 2-1. Present(Reference) PWR Fuel Cycle

Figure 2-2. Hybrid Enrichment Uranium Tails Fuel Cycle

Figure 2-3. Hybrid Enrichment Natural Uranium Fuel Cycle

Figure 2-4. Hybrid Enrichment Spent PWR Rod Fuel Cycle.

TABLE 2-1

HYBRID ENRICHMENT COST EFFECT ON PWR BUSBAR COST

	Present PWR Cycle	Privately Owned Hybrid		
		<u>U Tails</u>	<u>Natural U</u>	<u>Spent Rods</u>
Plant Capital Cost, 10^6 \$ (1978 Startup)	~700	2200	2250	2325
\$/kWe	580	1080	1020	880
Rated Electrical Power, MWe	1200	2030	2210	2640
Required Enrichment, w/o fissile	3.2	3.9	3.9	5.0
Hybrid Heavy Metal Production Rate, T/yr	----	62.7	68.5	52.2
Hybrid Enrichment Cost, \$/kg HM	----	1660	1160	345
Levelized Cost of Delivered PWR Fuel, \$/kg HM	2045	3215	2600	1205
Levelized PWR Fuel Cycle Cost				
\$/kg HM	2760	4300	3520	1400
mills/kwh	12	18	15	6
Levelized PWR Busbar Cost, mills/kwh	32	38	35	26

- The fuel undergoes significant burnup (energy release of $\sim 20\text{--}30$ GWd/THM) and extremely high fast fluence levels in the hybrid, which results in detrimental fission product poisoning for the subsequent PWR burn cycle and possible irreversible clad damage. This fission product buildup causes the higher enrichment (3.9-5.0 w/o) requirements.
- The hybrid enrichment process is relatively insensitive to the price of U_3O_8 (for the natural U case studied), since it does not require ~ 6 times the U feed to achieve the slightly enriched U product as in the isotopic enrichment process.
- The hybrid enrichment cost would decrease significantly as the electricity sales price increases, while the opposite is true for the isotopic enrichment process. Isotopic enrichment requires the purchase of electricity to operate the plant, while hybrid enrichment produces electricity as well as fuel enrichment.

During the course of this study, considerable sensitivity to several input values used in the economic analysis was found. This sensitivity results because the net hybrid operating cost charged against fissile fuel production is the difference of two large numbers, gross hybrid operating cost minus hybrid electric sales revenues. Figure 2-5 illustrates for the spent rods case the variation of hybrid enrichment costs and PWR busbar cost versus two key parameters, i.e., the fusion reactor capital cost and the electric sales rate used in the economic evaluation. By varying these parameters over reasonable ranges, the hybrid scenario PWR busbar cost varies from competitive to not competitive versus conventional PWR busbar cost, thus bracketing the conventional cost as shown in Figure 2-6.

Conclusions

In view of these results, this preliminary study shows sufficient potential incentive to proceed with further studies of fusion hybrid reactors in support of future fuel sources for PWR's. It should be noted that the technical prognosis for the demonstration of the requisite levels of physics and engineering performance required for the hybrid within the next twenty years are excellent. Assuming that these efforts are successful the earliest commercialization date for a hybrid system will probably lie in the ten-year period from 2000 to 2010.

Figure 2-5. Hybrid Enrichment Cost Sensitivity to Major Variables - Spent Rod Case

Figure 2-6. Hybrid Enrichment Cost Sensitivity to Electricity Sales Rate.

There are a number of issues that require more in-depth attention than was possible in the limited time available for the present study. Thus, the following issues are recommended for follow-on work:

- The effects of radiation damage to the cladding and fuel during the extended lifetime require analysis. The possibility and limitations of venting and/or baking the fuel rods needs to be investigated. It is conceivable that soaking the fuel rods at a temperature below that at which clad damage would occur may relieve radiation damage effects and reduce the clad stress levels.
- The removal of fission products from the fuel between irradiations could have a significant effect on its performance. A soaking procedure may be conceivable for driving out fission products.
- Since the economics are rather sensitive to the electrical power production of the hybrid, the production and consumption estimates must be examined closely. The models in COAST need to be re-examined to confirm an accurate treatment of these parameters.
- Further optimization of the hybrid design should be made, specifically for a first generation commercial application.
- The variation in concentration of fissile fuel along a rod irradiated in the hybrid should be determined. Variations from rod to rod should also be calculated. Fuel management schemes should be evaluated to achieve a more uniform concentration and reduce fuel residence time in the hybrid.
- Methods of achieving tritium self-sufficiency, including the possibility of producing tritium in the PWR, should be evaluated.
- Reprocessing scenarios should be evaluated (economically) and the more promising cases could be reviewed in more depth.
- Advantages of various fuel/forms, e.g., microspheres, U metal, thorium, should be evaluated for economic improvements and technical feasibility.

The significance of these results lies not so much in the absolute magnitude of the energy cost estimates but in their relatively close proximity to present day generation costs. Considering the most probable economic factors between now and the earliest commercialization date for a hybrid system (the period from 2000 to 2010, it seems likely that the availability of low cost natural uranium can be expected to decrease, isotopic enrichment costs should increase and overall electrical generation costs should increase. On this basis the competitive position of the hybrid should improve.

3.0 HYBRID REACTOR CONCEPT AND PARAMETERS

3.1 HYBRID REACTOR DESIGN CONCEPT

The hybrid reactor concept used in this study is characterized by the parameters given in Table 3-1. These are the parameters that are directly applied in the nuclear analyses in Section 4.0. The concept used for the economic study assumes an ignited plasma, tokamak hybrid reactor designed for fissile fuel and electric power production. Since the hybrid would be used as a fuel enrichment plant, it would be kept "on-line" at full capacity to the maximum extent possible. The parameters are based on commercial projections of the Demonstration Tokamak Hybrid Reactor⁽²⁾. The conceptual drawing of DTHR is shown in Figure 3-1.

TABLE 3-1
HYBRID REACTOR REFERENCE PARAMETERS

Major Radius	5.2 m
Minor Radius	1.2 m
Plasma Elongation	1.6
Neutron Wall Loading	2 MW/m ²
Plasma Duty Cycle	0.85
Plant Availability	0.70
Blanket Wall Coverage	58%
Blanket Fuel	UO ₂ pellets
Blanket Coolant	Dry Steam

DEMONSTRATION TOKAMAK HYBRID REACTOR

LEGEND

1 Plasma	7 Toroidal Field Coils
2 Vacuum Vessel	8 Inner Shield
3 Bundle Divertor	9 Outer Shield
4 Neutral Beam Injectors	10 Blanket Module
5 Vacuum Pumps	11 Cooling Headers
6 Poloidal Field Coils	12 Support Structure

Figure 3-1. Conceptual Trimetric View of the DTHR

3.2 HYBRID ENRICHMENT COST ANALYSIS

Evaluation of hybrid reactor enrichment economics required determining the cost of representative hybrid plants and establishing the performance of each plant. Various options for hybrid enrichment scenarios are possible; the hybrid plant could be costed on the basis of a privately owned plant using 18% fixed charge rate or as a publicly owned plant using 10% fixed charge rate. The publicly owned plant would assume no interest charges during construction, while the privately owned plant would. Both options were evaluated. All costs were in terms of 1978 dollars. For the three fuel types evaluated, spent PWR rods (1.34 w/o), rods fueled with uranium tails (0.25 w/o), and rods fueled with natural uranium (0.711 w/o), all used the same rod form. Therefore, only the power conversion system sizing affected the capital cost of the reference case plants evaluated.

The hybrid plant characteristics and capital costs are summarized in Table 3-2. The plant capital costs were established from a point design study⁽¹⁾ of a hybrid reactor plant concept developed by Westinghouse Fusion Power Systems for EPRI. That plant was slightly smaller ($R_o = 4.45$ m) than the reference concept used for the Commercial Tokamak Hybrid Reactor (CTHR) of this study. The costs were scaled based on a computer study done with COAST-4 after it was verified using the EPRI study design parameters. The performance data for each of the three plants were based on neutronic analyses discussed in Section 4 and summarized in Table 4-1. The annual operating costs and cost of enrichment are shown in Table 3-3. The hybrid operating and maintenance costs were scaled up 150% from typical, new (1978) nuclear power plant O & M levelized costs of 2 mills/kWh, since the hybrid reactor will be operated at higher power levels and has more expensive reactor equipment. The scheduled component replacement costs are handled as a separate item from the O & M costs, since several major components need periodic replacement. These costs were escalated and levelized over the 30 year hybrid plant lifetime.

TABLE 3-2
HYBRID CAPITAL COST AND PLANT CHARACTERISTICS

CAPITAL COST, 10^6 \$ (1978)

Publicly Owned Hybrid ^(a)	1700	1740	1800
Privately Owned Hybrid ^(b)	2200	2250	2325

PLANT CHARACTERISTICS

Input Fuel	U Tails	Nat. U	Spent Rods
Blanket Pwr (MW_t)	6140	6710	8000
Electric Pwr (MW_e)	2030	2210	2640
Electric Energy (kWh/yr) ^(c)	1.24×10^{10}	1.36×10^{10}	1.62×10^{10}
Initial Enrichment (%)	0.25	0.711	1.34
Final Enrichment (%)	3.9	3.9	5.0
Hybrid Residence (yr)	10	9.1	11.35
Heavy Metal Prod. (T/yr)	62.7	68.5	52.2
Fissile Prod. (kg/yr)	2380	2410	2100

- NOTES: (a) Publicly owned hybrid financing is based on a fixed charge rate of 10%/yr for capital depreciation, etc. No interest is charged during construction (i.e., Government funded project).
- (b) Privately owned hybrid financing is based on a fixed charge rate of 18%/yr for capital depreciation. Interest is charged during construction (S curve time averaged for physical plant and related indirect costs at 8% during the 7 year construction period).
- (c) Hybrid operating electric power needs are assumed to come from the hybrid shields and vacuum vessel cooling system conversion. The plasma is assumed ignited. The gross thermal efficiency is taken at 0.33. The plant capacity factor is estimated to be 0.70.

TABLE 3-3

HYBRID ENRICHMENT COSTS

ANNUAL OPERATING COST ^(a) 10 ⁶ \$ (1978)	PUBLICLY OWNED HYBRID ^(b)			PRIVATELY OWNED HYBRID ^(c)		
	U Tails	Nat. U.	Spent Rods	U Tails	Nat. U	Spent Rods
Input Fuel O & M ^(d)	37	41	49	37	41	49
Scheduled Component Replacements	68	68	68	68	68	68 x
Fixed Charges, Capital Depreciation ^{(b) (c)}	<u>170</u>	<u>174</u>	<u>180</u>	<u>396</u>	<u>405</u>	<u>419</u>
Gross Operating Cost	275	283	297	501	514	536
Electricity Sales ^(e)	<u>-233</u>	<u>-245</u>	<u>-292</u>	<u>-397</u>	<u>-435</u>	<u>-518</u>
Net Operating Cost	52	38	5	104	79	18
\$/kg HM	829	555	96	1660	1160	345
\$/g Fissile	22	16	2	44	33	9

NOTES: (a) Hybrid tritium fuel costs are assumed negligible based on a self-sustaining system.

(b) Publicly owned hybrid financing is based on a fixed charge rate of 10%/yr for capital depreciation, etc. No interest is charged during construction (i.e., Government funded project).

(c) Privately owned hybrid financing is based on a fixed charge rate of 18%/yr for capital depreciation. Interest is charged during construction (S curve time averaged for physical plant and related indirect costs at 8% during the 7 year construction period).

(d) Based on 3 mills/kWh levelized costing rate.

(e) Sales of hybrid generated electricity are assumed at the PWR busbar cost for a new (1978) nuclear power plant (32 mills/kWh as shown in Table 5-6) for a privately owned hybrid plant and at 18 mills/kWh for a publicly owned hybrid (assumed Government selected sales rates).

The conceptual commercial hybrid design used for Tables 3-2 and 3-3 could enrich fuel rods up to 2.4 m (~ 7.8 feet) long. Since the objective of this initial study was to "refresh" standard PWR fuel rods, which are 12 feet (~ 3.7 m) long, a parametric study was made using the COAST-4 code to evaluate cost and performance of larger tokamaks.

Parametric Analysis of Larger Tokamaks

Parametric calculations were made for the hybrid performance versus cost as a function of the major radius of the tokamak and the fusion neutron wall loading. Figure 3-3 shows that the production of fissile fuel increases at a faster rate than the capital cost of the hybrid physical plant as the neutron wall-loading increases. Thus, the capital cost per unit mass of fissile fuel produced decreases as the wall loading increases. In addition, the net average electrical power output was found to be proportional to the neutron wall loading. A conservative value for the wall loading of 2 MW/m^2 was selected based on the current technology of neutral beam injection and superconducting coils. Required neutral beam energy (E_b) and peak field at the toroidal field coil winding bore (B_{max}) to attain the specified wall loadings are shown. The magnitude of the quantities plotted should be considered as preliminary, but the trends are considered representative.

Figure 3-4 demonstrates in similar fashion that the capital cost per unit mass of fissile fuel produced decreases as the major radius, R , of the tokamak increases. The net average electrical power output increases linearly with R by a factor of 1.74 as the major radius increases from 5.2 m to ~ 7 m. The capital cost of the reactor and plant equipment and facilities can be scaled using the TCT hybrid study⁽¹⁾ costs. The TCT hybrid cost is scaled up as follows:

$$\text{CTHR} = \$ 1.8 \text{ B} \left[\frac{R^2}{4.45^2} \right]^{0.625}$$

By this cost scaling, for $R_0 = 5.2 \text{ m}$, the CTHR capital cost is \$2.2 Billion.

Figure 3-3. Hybrid Reactor Physical Plant Cost and Annual Fissile Fuel Production as a Function of Neutron Wall Loading For $R_0 = 5.2\text{m}$.

Figure 3-4. Hybrid Physical Plant Cost and Annual Fissile Fuel Production as a Function of Major Radius for a Neutron Wall Loading of 2 MW/m^2 .

It was determined that a CTHR with $R_0 = \sim 6.9$ could accommodate the 12 foot rods in three module locations around the outer half of the plasma as shown in Figure 3-2. The performance of the larger reactor is compared to the performance of a CTHR with $R_0 = 5.2$ m in Table 3-4. It can be seen from Table 3-4 that an economic improvement (\$/kgHM) of around 30% could be achieved with the larger reactor. This comparison was made using a near-ignition plasma operating mode based on the DTHR plasma physics (plasma $Q \sim 6$) to give a more conservative comparison than would be obtained if an ignited plasma were assumed (as was done in Table 3-2). A near-ignition plasma requires several hundred megawatts of electricity to operate the neutral beam injectors, thus reducing the electricity available for sale. Thus, the net operating cost shown in Table 3-4 (shown for the U tails case only) was higher than the Table 3-3 cost for the 5.2 m reactor using tails. The reactor, however, can be designed to be operable in either mode.

Hybrid Enrichment Cost Sensitivities

The hybrid enrichment costs are quite sensitive to the selling price and amount of electricity generated by the hybrid plant as can be seen by comparing the \$1660/kgHM from Table 3-3 (privately owned, U tails case) to the \$3733/kgHM ($R_0 = 5.2$ m column) from Table 3-4. This cost difference is the result of $\sim 4 \times 10^9$ kWh/yr less electricity for sale. These sensitivities are presented and discussed in Section 5.0. The results of the hybrid cost analysis from Table 3-3 are used in the Fuel Cycle Cost (FCC) analyses which are presented in Section 5.0.

Further Parametric Study Required

Parametric effects of varying the neutral beam power, plasma temperature, plasma elongation and other quantities are being studied. The results can be used to establish a more optimized hybrid reactor concept. Although dry steam was assumed as the blanket coolant in the neutronic analyses, subsequent work (on a similar ThO_2 concept) has indicated that the performance may be improved by going to a boiling water cooled blanket with a radial coolant density distribution (radial flow through vertical fuel rods). Thus, parametric studies of various blanket/power conversion systems should also benefit the hybrid performance and economics.

Figure 3-2. Hybrid Reactor Cross-Section for PWR Fuel Rod Enrichment

TABLE 3-4

HYBRID REACTOR PARAMETRIC ANALYSIS
(CTHR, Privately Owned, U Tails Fuel)

Plant Characteristics

R_0 , m	5.2	6.5	6.7 ^(a)	6.93
a, m	1.2	1.5	~1.5	1.6
Wall Loading, MW/m ²	2	2	2	2
NBI Energy, keV	180	200	~210	206
Initial Fuel Load ^(b) , Tonnes HM	600	900	950	1000
Fissile Prod., kg/yr	2300	3550	3700	4000
Electricity Prod. ^(c) , (kWh/yr)	8.28×10^9	1.26×10^{10}	1.33×10^{10}	1.43×10^{10}
Capital Cost, \$M (1978)	2200	2900	3000	3200

Annual Operating Cost, 1978 M \$

O & M (3 m/kWh)	25	38	40	43
Scheduled Replacements	68	92	95	99
Fixed Charge Rate (18%)	396	522	540	576
Gross Hybrid Operating Cost	489	652	675	718
Electricity Sales ^(d)	-265	-403	-426	-458
Net Hybrid Operating Cost	224	249	249	260
\$/kg HM ^(e)	3733	2767	2621	2600

NOTES: (a) Parametric curve interpolation.

(b) Based on fuel from uranium tails at 0.25 w/o fissile.

(c) Assumes near-ignition plasma concept ($Q \sim 6$),
(i.e., increased power to operate hybrid and reduced power to sell).

(d) Based on electricity sales at 32 mils/kWh.

(e) Based on initial fuel load and assumed 10 year irradiation cycle.

4.0 NUCLEAR ANALYSES

4.1 HYBRID ENRICHMENT (REFRESH) OF SPENT PWR FUEL

Spent fuel from a PWR has a burnup of 33 GWd/T and consists of 1.34 w/o fissile fuel of which 0.71 w/o is ^{235}U and 0.63 w/o is the sum of ^{239}Pu and ^{241}Pu . The spent fuel rods are placed in the hybrid blanket, but in a tighter lattice than used in the standard PWR fuel bundle. The steam cooled blanket is 0.51 m thick and its composition is 53 v/o fuel, 21 v/o Zr, and 24 v/o steam at a density of 0.064 gm/cm^3 (4 lb/ft^3). The blanket module is divided into three zones, each 18 cm thick and containing $\sim 200 \text{ T}$ (tonnes) of uranium and plutonium. Initially, the blanket is irradiated until the zone nearest the plasma reaches an enrichment of total fissile fuel of 5 w/o. This zone is then replaced by the fuel that had been in the middle zone and the fuel that had been in the last zone is moved into the middle zone. A new batch of spent fuel is moved into the last or outermost zone. This procedure is repeated until an equilibrium cycle is approached where every 3.77 years one batch of fuel is removed and the other batches are advanced one zone with a new batch placed in the outermost zone. Thus, the average batch residence time in the hybrid is $3 \times 3.77 \text{ years} = 11.35 \text{ years}$ to enrich to 5 w/o. The buildup of fissile content with time is shown in Figure 4-1. A summary of the analyses is given in Table 4-1. Note that a net 2100 kg of fissile fuel is produced per year and that the amount of fuel re-enriched will provide 65% of the initial loading for a 1 GWe PWR or reloads for ~ 2 PWR's. This compares to 6 - 8 LWR reloads if Pu recycle were assumed. In enriching the fuel to 5 w/o, the burnup in the hybrid is 29.6 GWd/T which, when added to the initial 33 GWd/T burnup in the PWR, gives a total of 62.6 GWd/T prior to re-inserting into the PWR. The fissile content, after refreshing the fuel, is 0.315 w/o ^{235}U , and 4.69 w/o ^{239}Pu plus ^{241}Pu . The average thermal power produced once equilibrium is established is 8 GW_t ; this quantity is important for the economic study. Further details on the nuclear analysis of these blankets are presented in reference 4.

Figure 4-1. Equilibrium Cycle Enrichment for Three UO_2 Fuel Compositions

TABLE 4-1
HYBRID ENRICHMENT NEUTRONIC DATA

	<u>Uranium Tails</u>	<u>Natural U</u>	<u>Spent PWR Rods</u>
Initial Fissile Enrichment, w/o	0.25	0.711	1.34
Required ^(e) Fissile Enrichment, w/o	3.9	3.9	5.0
Fuel Volume (53 v/o), m ³	70.8	70.8	70.8
Fuel Density - BOL, g/cm ³	9.06 ^(a)	9.06 ^(a)	8.59 ^(b)
Fuel Loading - BOL, Tonnes	642 ^(a)	642 ^(a)	608 ^(b)
Avg. Net Fissile Enrich. Rate, w/o/yr.	0.365	0.349	0.323
Irradiation time, yr.	10.0	9.1	11.35
Fuel Density - EOL, g/cm ³	8.85 ^(b)	8.81 ^(b)	8.34 ^(b)
Fuel Loading - EOL, Tonnes	627 ^(b)	623 ^(b)	590 ^(b)
HM Discharge Rate, Tonnes/yr.	62.7 ^(b)	68.5 ^(b)	52.2 ^(b)
Net Fissile Fuel Production, kg/yr.	2380 ^(c)	2410 ^(c)	2100 ^(c)
Duty Cycle Averaged Blanket Power, MWt	6140	6710	8000
Initial PWR ^(d) Loadings per yr.	0.78	0.86	0.65
PWR Reloads (1/3 core) per yr.	2.35	2.57	1.96
Final Fissile Content, ~ w/o			
²³⁵ U	0.12	0.38	0.31
²³⁹ Pu	3.67	3.43	4.48
²⁴¹ Pu	0.11	0.09	0.21
Fissile Enrich. Rate/Zone, w/o per yr.(net)			
Front	0.527	0.515	0.462
Middle	0.386	0.375	0.353
Back	0.182	0.156	0.155
Discharge Burnup, MWd/T ^(b)	22,800	20,800	29,600

(a) U

(b) U + Pu

(c) Fissile Pu

(d) 1000 MWe rated plant size

(e) To achieve ~ 33 GWd/THM burnup in the PWR

4.2 HYBRID ENRICHMENT OF NEW PWR FUEL

Calculations have also been performed for the initial enrichment of PWR fuel starting with uranium oxide rods composed of tails or natural uranium. The results of these calculations are also given in Figure 4-1 and Table 4-1. In these cases, since there has been no prior burnup of the fuel when placed in the hybrid blanket, it was estimated that an enrichment of 3.9 w/o would suffice (as compared to 5 w/o for the spent fuel). Note that the required irradiation times are quite similar for each case in Table 4-1 (9-11 years). The fluences that the fuel are subjected to in the hybrid lie in the range 0.5×10^{23} to 1.0×10^{23} n/cm² for $E > 0.1$ MeV. The fluences experienced in the PWR are relatively small $< 1 \times 10^{22}$ n/cm². For the hybrid blanket, when fuel composed of tails is irradiated over 10 years to an average enrichment of 3.9 w/o, $k_{\text{eff}} = 0.62$ for the steam coolant and $k_{\text{eff}} = 0.87$ under accident conditions when the steam is replaced by water.

The PWR core performance achievement was normalized at 34 GWd/T burnup for each of three hybrid produced fuels. Thus, the data characterized in Table 4-1 for fuels obtained from uranium tails, natural uranium, and spent PWR rods will all result in the same PWR burnup (on an equal energy basis). Following the burnup of the refreshed spent fuel rods by 34 GWd/T, it was noted that ~ 2.5 w/o of the fissile fuel remains. However, credit for this amount of fissile fuel was not taken in the economic study. If these fuels were left in the hybrid for shorter time periods, a different energy basis for PWR burnup would have had to be developed (i.e., < 34 GWd/T). For example, if fuel rods consisting initially of uranium tails are irradiated for 3, 5, 7, 8.5, 9.25, and 10 years, they are capable of achieving burnups in a PWR of 8, 17, 25, 30, 32, and 34 GWd/T, respectively.

Calculations on the use of the hybrid enriched fuel in a PWR indicated that a significant penalty is imposed on the required fissile enrichment due to the presence of fission products in the fuel. It is thus of interest to investigate whether a significant portion of the fission product parasitic loss could be avoided by bleeding off the gaseous fission products or possibly baking the

rods between irradiation in the hybrid and PWR. A preliminary estimate indicated that the gaseous fission products (mostly Kr and Xe) account for less than ten percent of the total fission product absorption cross section. Most of the absorption comes from various samarium and other rare earth isotopes, which occur in small amounts but have extremely high cross sections. Hence, removing the gaseous fission products will not have much of an effect on the nuclear performance of the fuel in the PWR although it could still be beneficial in reducing the clad stresses. Baking to remove fission products may not be beneficial since most of these detrimental isotopes are in stable solution with the UO_2 . A more optimum scenario than the three cases studied may include mechanical or chemical reprocessing after hybrid enrichment to eliminate these unwanted isotopes and thereby reduce the enrichment requirement and the irradiation time in the hybrid.

5.0 ECONOMIC POTENTIAL OF HYBRID ENRICHMENT

The use of a fusion hybrid reactor plant for PWR fuel "enrichment" differs in several significant ways from conventional isotopic enrichment processes. The fissile material in hybrid "enrichment" can be manufactured from fertile material rather than requiring a concentration of fissile materials. This is important because manufactured fissile material has no current free market value. The "enrichment" in the hybrid can actually be performed after the base material is fabricated into fuel rods. The "enrichment" process in the hybrid is accompanied by the generation of significant amounts of thermal energy. Enriching new or depleted uranium with the hybrid yields about the same amount of thermal energy as the fuel will produce during two to three years residence in the PWR. The calendar time required for hybrid enrichment to levels needed for a three-year PWR cycle is 9 to ~ 11 years for the simple scenarios studied to date. This contrasts with the two months required in a diffusion plant for enriching by concentration. This difference, the long residence time for hybrid enrichment, requires that the economics be calculated very carefully because of the long lead time for investments which it creates. However, the throughput of uranium feed required by isotopic enrichment plants is reduced to ~ 1/6 for the hybrid process, thus making the enrichment fuel cycle cost scenario relatively insensitive to the fertile material cost.

At the present stage of the development of the hybrid system, the design variants available are great and work has not been completed to establish optimal parameters. Therefore, a conservative near-term reference design, which could actually be built within a decade was selected. Larger machines were evaluated which could produce more attractive economics. This is true not only because of economics of scale, but because spacial constraints are relaxed in larger sizes, yielding proportionately greater blanket volume and higher power output. For this economic study, it was assumed that the hybrid plant was already built and put on the line in 1978. Similarly, the reference nuclear power plant data was averaged from actual plants coming on line in the 1978 time frame.

The economics of the hybrid system can be evaluated in many ways. These preliminary studies treat the hybrid as separate from the PWR, providing enrichment service analogous to the present isotopic enrichment service. Figure 5-1 illustrates the present enrichment cycle from ore to delivery of fuel assemblies to the PWR plant and similar cycles for hybrid enrichment. Note that the PWR owner is assumed to own the fuel materials all the way through each alternate cycle. It was also assumed that there will be no reprocessing, so that there is no intrinsic value for plutonium. This permitted looking mainly at the head end of the fuel cycle, up to the point at which fuel enters the PWR. The back end of the fuel cycle was normalized to a "throw-away" fuel cycle by assuming no U or Pu credit and assigning similar charges for spent rod shipping and disposal to the typical nuclear plant reference and the three hybrid cases studied.

5.1 REFERENCE PWR NUCLEAR PLANT

Table 5-1 illustrates the delivered cost of fuel, enriched by the gaseous diffusion process, to the PWR owner in 1978. The new contracts value of uranium (40 \$/lb U_3O_8) has been used. The carrying charge rate (10%) represents an interest on a temporary loan comparable to interest during construction for a plant and represents an average rate the PUC would allow the utility to use. Each investment was de-escalated by 6% per year to the time the investment would be made. This enabled all costs to be at a 1978 dollar value basis. The investment and carrying charges were then levelized over the 30 year life of the plant to represent annual charges that the utility could pass on to the consumer. From Table 5-1, it can be seen that the reference cost for fuel delivered to PWR is presently ~ 2045 \$/kg HM.

5.2 HYBRID ENRICHMENT CHARGES

The hybrid enrichment facility will have fixed neutrons per unit of operating time and a fixed irradiation volume. Actual irradiation (enrichment) space would be sold on the basis of some formula not yet defined, taking into account integrated neutron dosage per unit time and heat generating capability of the material. For this initial economic evaluation, the net revenue requirements for annual hybrid operation were determined and divided by the annual discharge

PRESENT PROCEDURE

HYBRID FROM DEPLETED UF₆ OR NATURAL U₃O₈

HYBRID FROM SPENT LWR FUEL

Figure 5-1. Enrichment Scenarios for Delivered LWR Fuel

TABLE 5-1
COST OF DELIVERED FUEL TO PWR
ISOTOPIC ENRICHMENT UO_2 FUEL

	<u>"Front End" Fuel Cycle Costs^(a) (1978 \$/kg HM)</u>
Investment in U_3O_8 ^(b)	618
Carrying Charge on U_3O_8 for 13 months	67
Conversion of U_3O_8 to UF_6 ^(c)	18
Carrying Charge on Conversion for 11 months	2
Enrichment ^(d)	298
Carrying Charge on Enrichment for 9 months	22
Design and Fabricate Fuel Assembly ^(e)	117
Carrying Charge on Design and Fabrication for 6 months	<u>6</u>
Unlevelized Investment	1148
Levelized Investment ^(f)	2043
(Lifetime Levelizing Factor = 1.78)	

(a) Carrying charge rate on investment of 10% per year.

(b) Based on U_3O_8 @ \$40/lb*, 2.6 kg U feed/lb U_3O_8 , and 6.33 kg U feed/kg U product for a PWR requiring 3.17 w/o enrichment, assuming 0.25 w/o tails.

(c) Based on \$3/kg U^* in UF_6 and 6.33 kg U feed/kg product.

(d) 3.17 w/o with 0.25 w/o tails requires 4.17 SWU/kg U product; at \$75/SWU.*

(e) At \$120/kg U. *

(f) Escalated at 6%/year over 30 year plant lifetime and discounted at 10% to 1978 present worth.

* De-escalated by 6%/yr. to time of investment.

mass of fertile/fissile material to get the annual cost per kilogram of heavy metal produced in the hybrid. A simple cost of plutonium can be calculated by dividing the annual hybrid operating cost by the annual plutonium production. This calculation was shown on Table 3-3. Because of the long time periods between procurement of the fuel to go into the hybrid and the removal of the fuel, this calculation is of little practical use. The comparable quantity is not the cost of plutonium, but the cost of fuel assemblies delivered to the PWR facility.

Calculations for three different cases (uranium tails, natural uranium, and spent PWR fuel) were determined using two different fixed charge rates on capital (18% for private financing and 10% for public financing) shown in Table 3-3. Electrical generation utilized the time-averaged blanket power. Power to operate the hybrid reactor was assumed to come from the other heat sources (divertor, neutral beam, shielding, and vacuum vessel cooling systems).

It was noted from Table 3-3 that the two important factors in the annual cost are the electricity sales credit and the fixed charges on the capital cost. Since these two factors are of similar size in the private investment cases, the net annual cost can swing widely and even change sign as either capital cost or the busbar value of electricity are varied. It is also clear that for the postulated conditions in Table 3-2, the cost of enrichment in a public owned hybrid facility should be negative because of the energy credit. The sensitivity of the hybrid enrichment cost to several key factors is presented later in this section.

5.3 COST OF DELIVERED FUEL ASSEMBLIES

Tables 5-2 and 5-4 illustrate the effects of the various carrying charges during the residence time in the hybrid facility. In Table 5-2 with uranium tails as the fuel, the total cost to the PWR owner for delivered fuel is about 1.5 times the cost of conventional fuel. In Table 5-3 with natural uranium fuel, the costs of delivered fuel is about 1.3 times conventional fuel. In Table 5-4 with PWR spent fuel, the delivered cost of fuel is only about one-half the cost of conventional fuel, in spite of the fact that the

TABLE 5-2
COST OF DELIVERED FUEL TO PWR
HYBRID ENRICHMENT - U TAILS

	<u>"Front End" Fuel Cycle Costs^(a) (1978 \$/kg HM)</u>
Investment in UF ₆ ^(b)	3
Carrying Charge UF ₆ for 12 Years	6
Design and Fabricate Fuel Assemblies ^(c)	62
Carrying Charge Design and Fabricate for 11.5 Years	123
Shipping Irradiated Fuel ^(d)	22
Carrying Charges on Shipping for 0.7 Year	2
Reassembly of Fuel Pins for PWR ^(e)	59
Carrying Charge on Reassembly for 0.5 Year	3
Shipping Reassembled Fuel ^(d)	22
Carrying Charges on Shipping for 0.2 Year	1
Unlevelized Investment	<u>303</u>
Levelized Investment (Lifetime levelization factor = 1.78) ^(f)	540
Hybrid Irradiation Charge ^(g)	1660
Carrying Charge on Hybrid Irradiation	<u>1014</u>
Total Levelized Investment	3214

(a) Carrying charge rate on investment at 10% per year

(b) Based on tails of 0.25 w/o at \$5*/kg U.

(c) At \$120*/kg U.

(d) At \$22/kg HM*.

(e) AT \$60/kg HM*.

(f) Using 6%/year escalation, 10% discount rate and 30 year plant life.

(g) Enrichment cost from Table 3-3.

* De-escalated by 6%/year to time of investment.

TABLE 5-3
COST OF DELIVERED FUEL TO PWR
HYBRID ENRICHMENT - NATURAL U

	<u>"Front End" Fuel Cycle Costs^(a) (1978 \$/kg HM)</u>
Investment in U_3O_8 ^(b)	55
Carrying Charge U_3O_8 for 11.1 Years	103
Design and Fabricate Fuel Assemblies ^(c)	65
Carrying Charges Design and Fabricate for 10.6 Years	113
Shipping Irradiated Fuel ^(d)	22
Carrying Charges on Shipping for 0.7 Year	2
Reassembly of Fuel Pins for PWR ^(e)	59
Carrying Charge on Reassembly for 0.5 Year	3
Shipping Reassembled Fuel ^(d)	22
Carrying Charge on Shipping for 0.2 Year	1
	<hr/>
Unlevelized Investment	445
Levelized Investment(Lifetime levelization factor = 1.78) ^(f)	<hr/> 792
Hybrid Irradiation Charge ^(g)	1160
Carry Charge on Hybrid Irradiation	<hr/> 646
Total Levelized Investment	2598

(a) Carrying charge rate on investment at 10% per year

(b) Based on U_3O_8 at \$40/lb*.

(c) At \$120/kg U*.

(d) At \$22/kg HM*.

(e) At \$60/kg HM*.

(f) Using 6%/year escalation, 10% discount rate and 30 year plant life.

(g) Enrichment cost from Table 3-3.

* De-escalated by 6%/year to time of investment.

TABLE 5-4
COST OF DELIVERED FUEL TO PWR
HYBRID ENRICHMENT - SPENT PWR RODS

	<u>"Front End" Fuel Cycle Costs^(a) (1978 \$/kg HM)</u>
Vent Fuel Pins and Reassemble for Hybrid ^(b)	48
Carrying Charge on Reassembly for 12.9 Years	115
Shipping Reassembled Fuel ^(c)	11
Carrying Charge on Shipping for 12.6 Years	25
Shipping Irradiated Fuel ^(c)	22
Carrying Charge on Shipping for 0.7 Year	2
Vent Fuel Pins and Reassemble for PWR ^(b)	97
Carrying Charges on Reassembly for 0.5 Year	5
Shipping Reassembled Fuel ^(c)	22
Carrying Charge on Shipping for 0.2 Year	1
Unlevelized Investment	<u>348</u>
Levelized Investment (Lifetime levelization factor = 1.78) ^(d)	620
Hybrid Irradiation Charge ^(e)	345
Carrying Charge on Hybrid Irradiation	<u>240</u>
Total Levelized Investment	1205

(a) Carrying charge rate on investment at 10% per year.

(b) At \$100/kg HM*.

(c) At \$22/kg HM*.

(d) Using 6%/year escalation, 10% discount rate and 30 year plant life.

(e) Enrichment cost from Table 3-3.

* De-escalated by 6%/year to time of investment.

residence time is on the order of 11 years. It is obvious without preparing the tables that public ownership of the hybrid will yield a lower investment for hybrid enriched fuel for all three cases studied than with the present gaseous diffusion enrichment cycle.

Table 5-5 combines the delivered fuel investments of the previous four tables so that a comparison can be made as to where the relative gains and losses occur for the different cases. The large costs in the present PWR fuel rod cost are the uranium investment and the isotopic enrichment cost. The uranium investment cost is roughly half the cost and increases linearly with the price of U_3O_8 . The corresponding costs for the hybrid enriched fuels are much lower, so that the hybrid enrichment costs will rise much more slowly than the present system costs as the raw U_3O_8 price rises. The enrichment cost in the present PWR cycle is about one-third of the cost and rises with increasing electrical cost. The "enrichment" cost for the hybrid process dominates the delivered fuel costs for the three cases studied, but the cost will decrease with increasing electrical costs provided the hybrid is a seller, not a buyer, of electricity. This is clearly reflected by the lower enrichment cost for the spent rod case, which produced 20% to 30% more saleable electricity.

5.4 PWR FUEL CYCLE COST COMPARISON

Table 5-6 presents the effect that the hybrid enrichment cost has on the PWR busbar electricity cost. The three hybrid cases studied are compared to a typical 1978 nuclear power plant's fuel cycle cost. All data has been normalized to the "throw away" spent fuel rod basis. The results show that the re-enriched spent rod case using hybrid enrichment would be less costly than the present day nuclear fuel cycle cost reference, while the U natural and tails cases would be slightly more expensive. The hybrid generated electricity sales rate was based on the typical 1978 nuclear plant busbar cost (32 mills/kWh). The sensitivity of the hybrid enrichment costs to the assumed electricity sales rate are shown in Figure 5-2 and discussed in the following paragraphs.

TABLE 5-5
COMPARISON OF INVESTMENT IN DELIVERED PWR FUEL
(1978 \$/kg HM)

	<u>Present PWR Rods</u>	<u>Privately Owned Hybrid</u>		
		<u>U Tails</u>	<u>Natural U</u>	<u>Spent Rods*</u>
Investment in U	618	3	55	N.A.
Carrying Charge	67	6	103	
Conversion to UF ₆	18	N.A.	N.A.	N.A.
Carrying Charge	2			
Enrichment	298	1660	1160	345
Carrying Charge	22	1014	646	240
Design and Fabricate Rods	117	62	65	N.A.
Carrying Charge	6	123	113	
Ship Irradiated Fuel Rods	N.A.	44	44	55
Carrying Charge		3	3	28
Reassembly of Rods (Venting Spent Rods)	N.A.	59	59	145
Carrying Charge		3	3	120
Unlevelized Investment	1148	2977	2251	933
Levelizing Adjustment	895	237	347	272
Total Levelized Investment	2043	3214	2598	1205

* Credit for the initial Spent Rod Disposal not required is handled with the back end fuel cycle costs.

TABLE 5-6

HYBRID ENRICHMENT COST EFFECT ON PWR BUSBAR COST

	Present PWR Cycle	Privately Owned Hybrid		
		U Tails	Natural U	Spent Rods
Capital Cost, 10^6 \$	~700	2200	2250	2325
(1978 Startup) \$/kWe	580	1080	1020	880
Rated Electrical Power, MWe	1200	2030	2210	2640
Required Enrichment, w/o ^(a)	~3.2	3.9	3.9	5.0
Hybrid Heavy Metal Discharge Rate, T/yr	----	62.7	68.5	52.2
Hybrid Enrichment Cost, \$/kg HM	----	1660	1160	345
Cost ^(b) of Delivered PWR Fuel, \$/kg HM	2045 ^(c)	3215	2600 ^(c)	1205
PWR Fuel Cycle Cost ^(d) , \$/kg HM	2760	4300	3520	1400
mills/kwh	12	18	15	6
PWR Capital + O & M Cost, mills/kwh	20	20	20	20
PWR Busbar Cost, mills/kwh	32	38	35	26

(a) Enrichment required to achieve ~ 33 GWD/THM burnup in the PWR.

(b) Carrying charges taken as 10% per year up to fuel delivery to PWR. Costs levelized using escalation rate at 6%/year and discount rate at 10%/year over 30 year plantlife.

(c) \$40/lb U_3O_8 de-escalated 6%/year to the time of investment.

(d) Fuel carrying charges during three-year PWR burnup taken at 17% year. Assumes "throw-away" fuel cycle for PWR (no reprocessing costs, no U or Pu credit, \$22/kg HM for shipping spent rods and \$100/kg HM for disposal of spent rods). Costs levelized using 6%/year escalation rate and 10%/year discount rate for 30 year plantlife.

Figure 5-2. Hybrid Enrichment Cost Sensitivity to Electricity Sales Rate.

5.5 HYBRID ENRICHMENT COST SENSITIVITIES

The sensitivity of the hybrid enrichment cost to the hybrid busbar electricity sales rate, the hybrid capital cost, the fixed charge rate, the percent of converted blanket power required to operate the hybrid (and thus, not saleable as electricity), and the hybrid plant capacity factor have been analyzed and the results are presented in Figures 5-2, 5-3, 5-4 and 5-5. The highlights of these analyses are discussed below.

From Figure 5-2, it can be seen that the spent PWR fuel rod case is the most sensitive to the hybrid generated electricity sales rate, while the natural uranium and tails cases have a similar sensitivity (curves nearly parallel). The three hybrid enrichment (reference) cases studied used 32 mills/kWh based on a typical 1978 Nuclear Power Plant busbar rate. Obviously, the privately owned hybrid enrichment plants would not be competitive if historical nuclear power plant busbar costs (15 mills/kWh in 1978) had been used. Both the natural U and U tails cases studied were less economical (shaded zone) than the present PWR enrichment process. Furthermore, the sales rate for electricity would have to fall to 24.5 mills/kWh for natural U and 20.5 mills/kWh for U tails before either option would be more economical than the spent rod case at those rates. The spent rod case studied was more economical than the present PWR enrichment process and the sales rate could drop to 30 mills/kWh before this relationship reversed. For the three reference cases studies, the U tails fuel rods were ~ \$500/kg HM higher than natural U rods, while the spent rods case was ~ \$800/kg HM lower than the natural U rods. However, all three cases studies resulted in the competitive cost point falling between \$750 to \$1,000 per kg HM, with the spent rod case competitive point at 30 mills/kWh, the U natural case at 34 mills/kWh, and the U tails case at 36 mills/kWh electricity sales rate.

Figures 5-3 and 5-4 show the sensitivities of U tails and natural U to various parameters affecting hybrid operating costs and electricity sales since these two factors have the greatest impact on hybrid enrichment costs. If the U tails enrichment costs were reduced by ~ \$500/kg HM, the sensitivity curves would be almost coincident. The cost difference is mostly attributed to the better thermal output from the U natural fuel (2210 MW_e vs. 2030 MW_e) which

Figure 5-3. Hybrid Enrichment Cost Sensitivities to Various Parameters for U Tails Fuel Rods.

Figure 5-4. Hybrid Enrichment Cost Sensitivities to Various Parameters for Natural Uranium Fuel Rods.

Figure 5-5. Hybrid Enrichment Cost Sensitivities to Various Parameters for Spent PWR Rods ("Refresh").

results in higher electricity sales income. As was shown in Table 5-5, the fuel carrying charge during hybrid irradiation also relates directly with the hybrid enrichment cost in determining the total fuel cycle costs. The natural U case required ~ 1 year less irradiation time and this factor amplifies the effect of the lower enrichment cost so that the total enrichment related investments are ~ \$1800/kgHM for natural U as compared to ~ \$2700/kgHM for U tails. The uranium fertile materials cost difference (\$5/kg for tails vs. \$104/kg for natural) results in ~ \$200/kgHM for delivered fuel costs (levelized) and thus is far less sensitive than the enrichment cost. Therefore, the enrichment related cost difference dominated the 3 mills/kWh spread in PWR busbar costs. The remaining sensitivities for the natural U or U tails cases are similar to, but must less significant than, those found for the spent rods case, which are discussed in the following paragraph.

Figure 5-5 shows the spent PWR fuel rod case sensitivities of the hybrid enrichment cost to key cost related parameters. Since this case had no fertile material cost or initial fuel carrying charges, the resulting PWR busbar cost for this fuel cycle is extremely sensitive to the enrichment cost and therefore, to the parameters shown in Figure 5-5. The cross-over point for all the curves represents the "reference" case parameters on the abscissa, (i.e., \$2325 M capital cost, 0.18 fcr, 0 power from blanket, 0.7 capacity factor and 32 mills/kWh electricity sales rate). The effects of varying these parameters over reasonable ranges are shown in the following examples.

- An increase of 25% in hybrid capital cost would increase the hybrid enrichment cost by a factor of 6.75, which increases the PWR busbar cost by a factor of 1.65 (26 to 43 mills/kWh).
- A 2% higher fixed charge rate for depreciating capital costs would increase the hybrid enrichment cost by a factor of 3.55, which increases the PWR busbar cost by a factor of 1.3 (26 to 34 mills/kWh).
- If 10% of the electricity generated by the hybrid is required to operate the plant, the cost of hybrid enrichment would increase by a factor of 3.8, which increases the busbar cost by a factor of 1.33 (26 to 34.5).
- A decrease in the hybrid plant capacity factor from 0.7 to 0.6 would increase the hybrid enrichment cost by a factor of 5.1, which increases the busbar cost by a factor of 1.6 (26 to 41.5).

- An increase in the hybrid generated electricity sales rate by 2 mills/kWh would reduce hybrid enrichment cost by 180%; an increase of 25% would reduce the enrichment cost 680%. If this were the only factor changing, a 1 mill/kWh increase would eliminate hybrid enrichment costs.

The preceding examples have looked at the sensitivities from a predominantly negative viewpoint. However, it can be seen from Table 5-6 that the cost of delivered fuel (1205 \$/kgHM) could almost double and still be competitive with the present PWR cycle (2045 \$/kgHM). Thus, a 2% change in fixed charge rate or a 10% drop in electrical power output would produce a change in the competitiveness of this case from somewhat positive to slightly negative. Only major changes like a 25% increase in capital cost would affect the general competitive status of the spent rod case and even then, the change could be offset by a similar change in electricity sales rate. Thus, the two most sensitive parameters, capital cost and electricity sales rates, have offsetting effects. This means that inflation or escalation changes in the next decade should not change the relative competitive position of the spent rod case by any significant amount.

6.0 REFERENCES

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