WFPS:TME-80-016
DECEMBER 31, 1980
UC 20d

THE FEASIBILITY OF RECYCLING THORIUM IN A FUSION-FISSION HYBRID/PWR SYMBIOTIC SYSTEM

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COOPERATIVE GRADUATE EDUCATION PROGRAM IN FUSION TECHNOLOGY
ADMINISTERED FOR THE U.S. DEPARTMENT OF ENERGY
BY THE WESTINGHOUSE ELECTRIC CORPORATION
CONTRACT ~~EG-77-C-02-4231-A000~~
AC02-77ET51010

DISCLAIMER

ACKNOWLEDGEMENT

The author wishes to gratefully acknowledge the advice and guidence of Harold Garber and Dr. Gordon Gibson at Westinghouse Fusion Power Systems Department and Dr. Hans Fleischman at Cornell University. This study is indebted to the many sources of information listed in the references and especially Richard Duda of Westinghouse Fuel Services for information on fuel fabrication costs. The staff and fellow students at Fusion Power Systems Department are appreciated for their help and for making a pleasant stay at Westinghouse during the initial preparation of this manuscript. In this regard a special thanks goes to Yvonne Harlow for typing the manuscript and for her continual confidence and support. The author also wishes to thank Dr. Daniel Klein for his useful comments during initial presentations of this material and for his efforts in making the program under which this work was done and my participation in this program possible.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield VA 22161

NTIS price codes
Printed Copy: A04
Microfiche Code: A01

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ABSTRACT

A study was made of the economic impact of high levels of radioactivity in the thorium fuel cycle. The sources of this radioactivity and means of calculating the radioactive levels at various stages in the fuel cycle are discussed and estimates of expected levels are given. The feasibility of various methods of recycling thorium is discussed. These methods include direct recycle, recycle after storage for 14 years to allow radioactivity to decrease, shortening irradiation times to limit radioactivity build up, and the use of the window in time immediately after reprocessing where radioactivity levels are deminished. An economic comparison is made for the first two methods together with the throwaway option where thorium is not recycled using a mass energy flow model developed for a CTHR (Commercial Tokamak Hybrid Reactor), a fusion fission hybrid reactor which serves as fuel producer for several PWR reactors. The storage option is found to be most favorable however even this option represents a significant economic impact due to radioactivity of 0.074 mills/kW-hr which amounts to $\$4 \times 10^9$ over a 30 year period assuming a 200 gigawatt supply of electrical power.

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1.0 INTRODUCTION

Thorium is currently being considered for use in a fusion-fission hybrid/PWR symbiotic system. The reference fuel cycle for this system is shown in Figure 1-1. The hybrid reactor serves as a fissile fuel producer for PWR's. Neutrons produced by fusion reactions convert thorium contained in a blanket surrounding the fusion device to fissile ^{233}U. The ^{233}U is then recovered by reprocessing the fuel and used to fuel PWR's.

Although the thorium/^{233}U fuel cycle appears attractive for many reasons[1], there has been some concern that the economic and environmental impact of significantly higher levels of radioactivity in this fuel cycle may make it less attractive than the ^{238}U/Pu fuel cycle[2]. Some work has been performed on the economic impact of high levels of radiation in the bred uranium[3,4,5]. This report, however, assesses the economic impact on the fuel cycle of radioactivity generated in thorium when it is irradiated in the hybrid reactor. In particular, this report focuses on whether and under what conditions thorium should be recycled in the hybrid reactor.

An economic comparison was made for the three options: throwaway, storage, and direct recycle. These options are described below.

- Throwaway - new thorium is purchased and the irradiated thorium is discarded (a small amount of the irradiated thorium can be used in the PWR's - the rest goes to geologic storage sites for permanent disposal);

- Storage - the irradiated thorium is stored for approximately fourteen years to allow radioactivity to decay to safe hands-on fuel fabrication levels and then it is recycled;

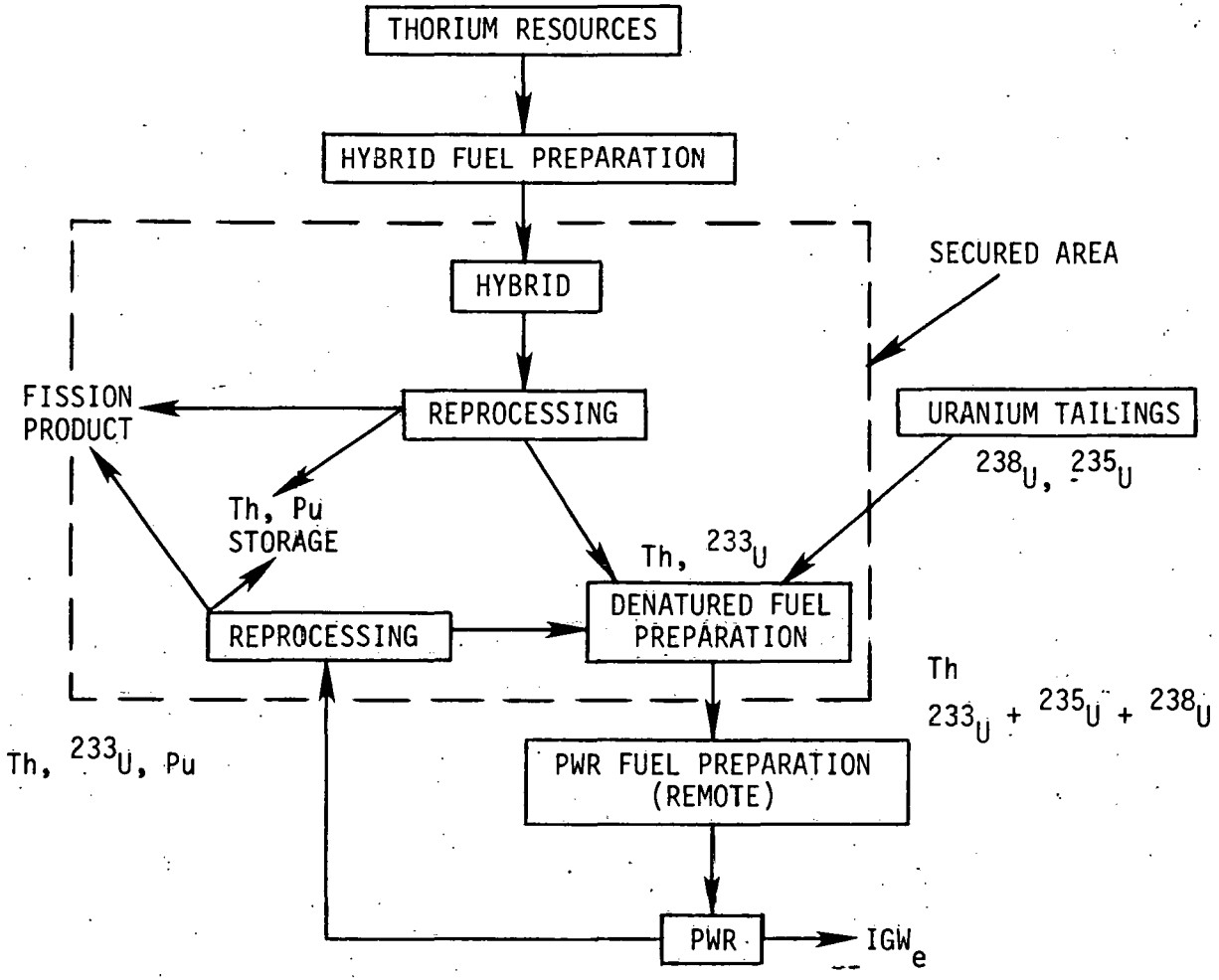

Figure 1-1. Reference Fuel Cycle.

- Direct Recycle - the thorium is immediately recycled using a more expensive remote fuel fabrication facility.

Direct recycle may also be possible using less expensive hands-on fuel fabrication techniques. The thorium radioactivity level would be low enough for hands-on fuel fabrication if the residence time of the thorium in the hybrid were short enough. Another possibility is that the thorium radioactivity level might be low enough for hands-on fuel fabrication if fabrication is performed immediately after reprocessing, since reprocessing removes radioactive decay daughters. This report examines these possibilities to decide if there is an economically feasible way to recycle the thorium and also to determine the economic penalty that the radioactivity of the thorium represents.

REFERENCES FOR SECTION 1.0

1. H. A. Bethe, "The Fusion Hybrid," Nuclear News, May 1978.

2. B. R. Leonard, Jr. and U. P. Jenquin, "The Quality of Fissile Fuel Bred in a Fusion Reactor Blanket," Presented at the Second Topical Meeting on: The Technology of Controlled Nuclear Fusion, September 21-23, 1976, Richland, Washington, Battelle Pacific Northwest Laboratories, BNWL-SA-5750, Richland Washington, 1976.

3. R. E. Brooksbank, J. P. Nichols, and A. L. Lotts, "The Impact of Kilorod Facility Operational Experience on the Design of Fabrication Plants for ^{233}U-Th Fuels," Proceedings of the Second International Thorium Fuel Cycle Symposium, Gatlinburg, TN, May 3-6, 1966; AEC 12 Symposium Series, Thorium Fuel Cycles, Division of Technical Information (February 1968).

4. J. D. Sease, R. B. Pratt, and A. L. Lotts, "Remote Fabrication of Thorium Fuels," Proceedings of the Second International Thorium Fuel Cycle Symposium, Gatlinburg, TN, May 3-6, 1966; AEC 12 Symposium Series, Thorium Fuel Cycles, Division of Technical Information (February 1968).

5. R. F. Duda, "Study of the Cost Impacts of Spiking Plutonium," Westinghouse Nuclear Fuel Division, Pittsburgh PA (1975).

2.0 SOURCES OF RADIOACTIVITY

The radioactive thorium isotopes produced in natural thorium, along with the reactions leading to their formation, are shown in Figure 2-1. Some impurities will also be present in irradiated thorium such as fission products and protactinium, however, reprocessing will reduce their contribution to the thorium radioactivity to relatively low levels.

Thorium-231 produced from (n,2n) reactions on ^{232}Th has such a short half-life (25.5 hrs) that it will practically disappear during the cooling period before reprocessing. The same holds true for ^{233}Th (22.2 m half-life) which is produced by (n,γ) reactions on ^{232}Th.

Thorium-233 can undergo a (n,γ) reaction to produce ^{234}Th. The ^{234}Th, which has a 24.1 d half-life, decays to ^{234}Pa emitting a 0.020 MeV β and a 0.093 MeV γ. The ^{234}Pa, which has a half-life of 1.175 m, decays to ^{234}U emitting a 2.35 MeV β and a 0.817 MeV γ. Thorium-234 is a significant source of radioactivity unless the cooling period before reprocessing is increased to about 400 days. A long cooling period however would increase the amount of ^{228}Th that would build up from the decay of ^{232}U (half-life of 74 years)

The decay chain for ^{228}Th (half-life 1.91 years) is shown in Figure 2-2. Thorium-228 contributes significant levels of γ activity due to its decay daughters ^{212}Bi, which emits a 2.2 MeV γ and ^{208}Tl, which emits a 2.6 MeV γ. The radioactivity due to ^{228}Th represents the major obstacle for recycling thorium in the hybrid.

Thorium-230 produced by the (n,3n) reaction on ^{232}Th is a low level α emitter (half-life 77,000 years), which decays to ^{226}Ra, which is also very toxic. Because of ^{230}Th, irradiated thorium will require long term containment such as geologic storage if it is not reused.

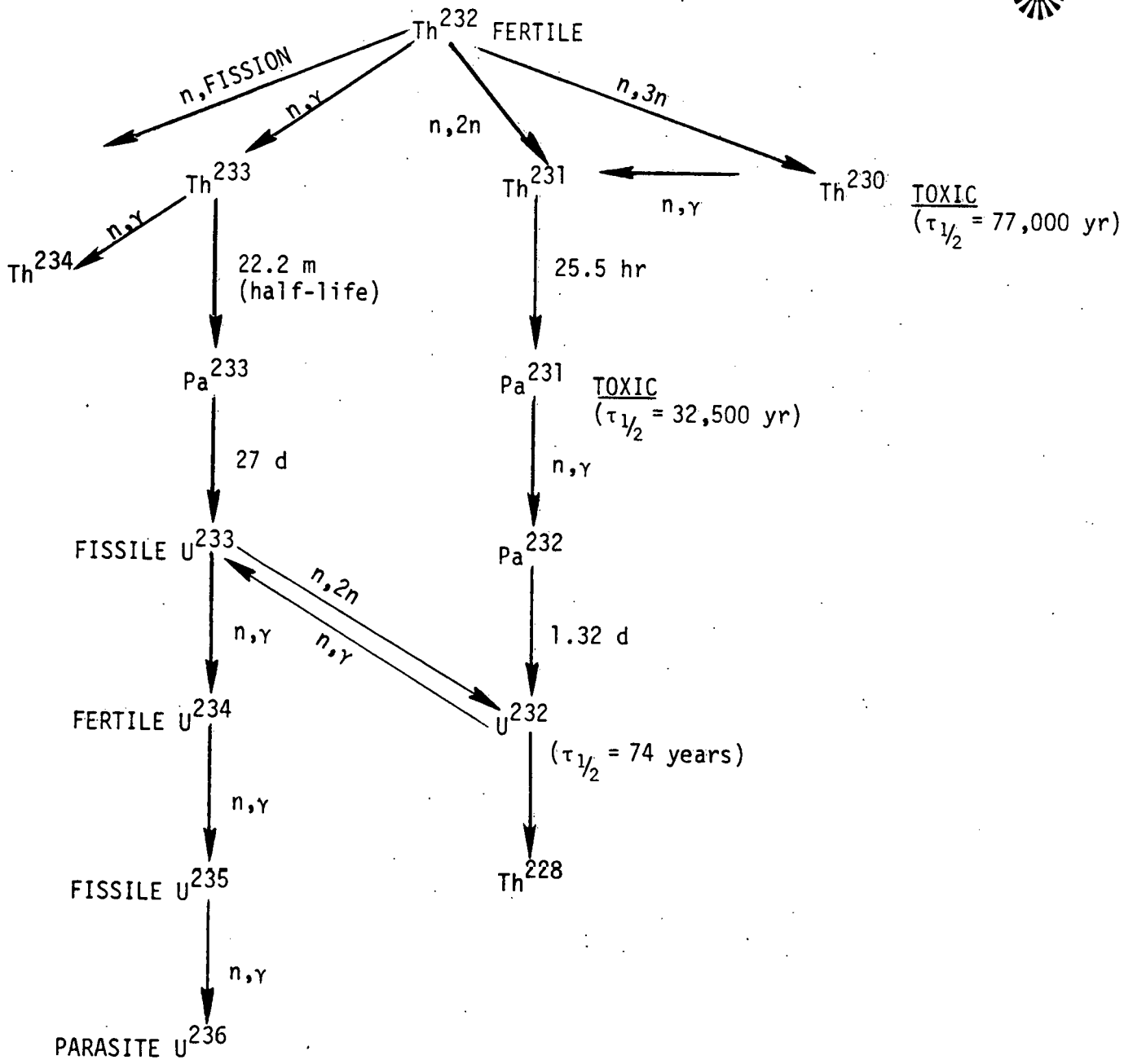

Figure 2-1. Nuclei Formed by the Irradiation of Thorium; Reactions Leading to Radioactive Thorium Isotopes.

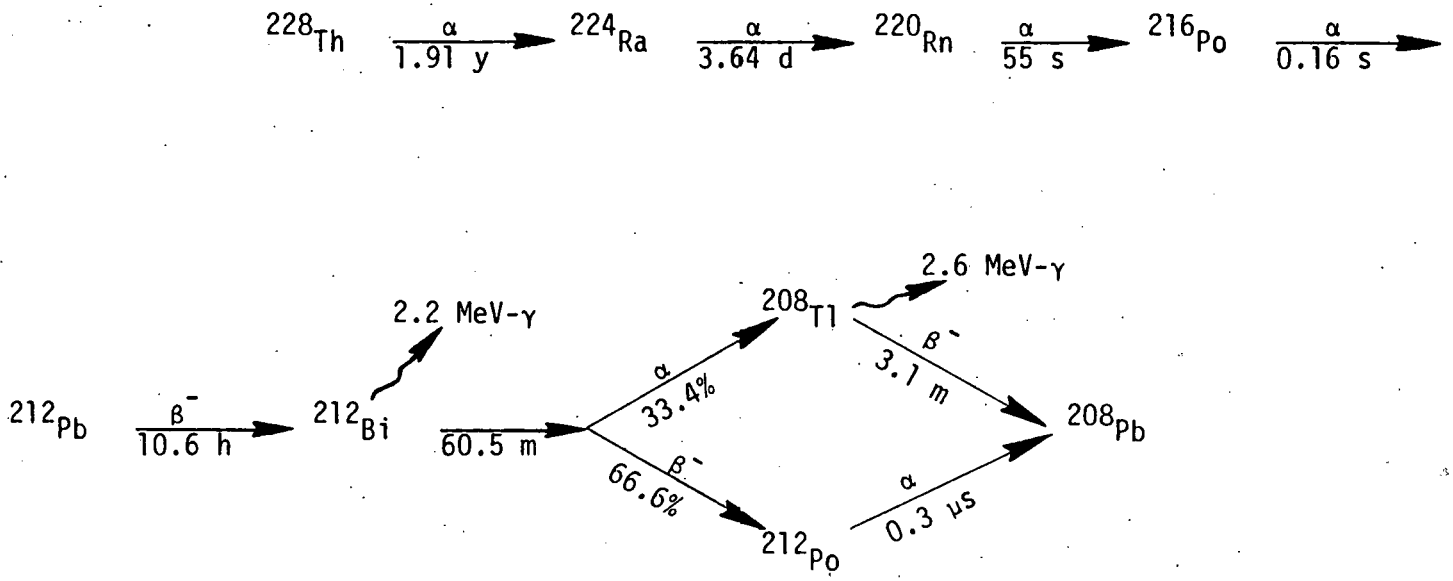

Figure 2-2. The ^{228}Th Decay Chain.

REFERENCES FOR SECTION 2.0

1. E. D. Arnold, "Radiation Hazards of Recycled ^{233}U Thorium Fuels," Proceedings of the Thorium Fuel Cycle Symposium, Gatlinburg, TN, December 5-7, 1962; United States Atomic Energy Commission Division of Technical Information TID-7650.

3.0 ESTIMATION OF ^{228}Th LEVELS IN HYBRID IRRADIATED THORIUM

Thorium-228 is produced as follows: the (n,2n) reaction on ^{232}Th produces ^{231}Th which decays to ^{231}Pa. This ^{231}Pa is converted by (n,γ) reactions to ^{232}Pa which decays to ^{232}U which then decays to ^{228}Th.

The basic equation describing ^{228}Th production is

$$\frac{d N_{08}}{dT} = -\lambda_{08} N_{08} + R(t) \qquad (3\text{-}1)$$

where N_{08} is the thorium-228 concentration, λ_{08} is the decay constant for ^{228}Th, and R(t) is the decay rate of the ^{228}Th precussor ^{232}U. The concentration of ^{232}U, as a function of irradiation time, has been calculated by Jenquin and Leonard[1] whose results are shown in Table 3-1.

TABLE 3-1

BUILDUP OF PROTACTIUM AND URANIUM IN A THORIUM HYBRID BLANKET

	IRRADIATION TIME, days					
ISOTOPE	10	25	50	100	200	400
	grams/MTHM*					
^{231}Pa	45.2	113	226	450	895	1770
^{233}Pa	10.4	21.7	33.2	42.4	45.7	45.7
^{232}U	0.0190	0.155	0.649	2.60	10.4	41.2
^{233}U	137	345	699	1410	2830	5560
^{234}U	0.0943	0.531	1.84	5.86	17.3	50.5
Total U	137	346	702	1420	2860	5660

*MTHM - metric tonnes of heavy metal

The ^{232}U production data can be fitted to a curve of the form

$$N_{22} = a_1 + a_2 t + a_3 t^2,$$

with t in units of days, by least squares analysis with the result

$$\begin{aligned} a_1 &= -0.169 \\ a_2 &= 9.92 \times 10^{-4} \\ a_3 &= 2.55 \times 10^{-4} \end{aligned}$$

Since the first two terms contribute little to the ^{232}U production over a three year period they are neglected and the data on ^{232}U is quite well represented by

$$N_{22} = 2.6 \times 10^{-4}\ t^2 \qquad (3\text{-}2)$$

Since the decay rate of ^{232}U is given by $R(t) = \lambda_{22} N_{22}(t)$, where λ_{22} is the decay constant for ^{232}U, equation 3-1 describing thorium-228 production becomes

$$\frac{d N_{08}}{dT} = -\lambda_{08} N_{08} + \lambda_{22} (2.6 \times 10^{-4})\ t^2$$

Performing a Laplace transformation to the s plane gives

$$s \mathcal{L} N_{08} = -\lambda_{08} \mathcal{L} N_{08} + \lambda_{22} (2.6 \times 10^{-4}) \frac{2}{s^3}$$

or

$$\mathcal{L} N_{08} = \frac{\lambda_{22} (2.6 \times 10^{-4})\ 2}{s^3 (s + \lambda_{08})}$$

Expanding by partial fractions gives

$$\mathcal{L} N_{08} = \frac{\frac{\lambda_{22} (2.6 \times 10^{-4})\ 2}{\lambda_{08}}}{s^3} - \frac{\frac{\lambda_{22} (2.6 \times 10^{-4})\ 2}{\lambda_{08}^2}}{s^2}$$

$$+ \frac{\frac{\lambda_{22} (2.6 \times 10^{-4})\ 2}{\lambda_{08}^3}}{s} - \frac{\frac{\lambda_{22} (2.6 \times 10^{-4})\ 2}{\lambda_{08}^3}}{s + \lambda_{08}}$$

Performing an inverse transformation gives

$$N_{08} = \frac{\lambda_{22}}{\lambda_{08}}(2.6 \times 10^{-4})\, t^2 - \frac{\lambda_{22}}{\lambda_{08}^2}(2.6 \times 10^{-4})\, 2t + \frac{\lambda_{22}}{\lambda_{08}^3}(2.6 \times 10^{-4})\, 2 - \frac{\lambda_{22}}{\lambda_{08}^3}(2.6 \times 10^{-4})\, 2\, e^{-\lambda_{08} t} \quad (3\text{-}3)$$

Since λ_{22} and λ_{08} are known,

$$\lambda_{22} = 2.56396 \times 10^{-5} \quad (T\ 1/2 = 74 \text{ years})$$
$$\lambda_{08} = 9.9337 \times 10^{-4} \quad (T\ 1/2 = 1.91 \text{ years})$$

equation (3-3) can be used to determine the ^{228}Th concentration as a function of irradiation time. These results are presented in Table 3-2. The following conversion was used to obtain results in terms of curies/gram of heavy metal:

$$\left[\frac{Ci}{gm}\right] = \frac{\lambda_{08}\ s^{-1}}{3.7 \times 10^{10}\ \frac{\text{disintegrations/s}}{Ci}} \times \frac{N_A \text{ atoms/mole}}{A \text{ gm/mole}}$$

where

$N_A = 6.02 \times 10^{23}$ (Avagadro's number)
$A = 228$ (Atomic Mass of ^{228}Th)
$\lambda_{08} = 1.15 \times 10^{-8}\ s^{-1}$

The results are also plotted in Figure 3-1.

The ^{228}Th level in hybrid irradiated thorium also depends on the length of the cooling period before reprocessing begins and the length of the time delay before recycling takes place.

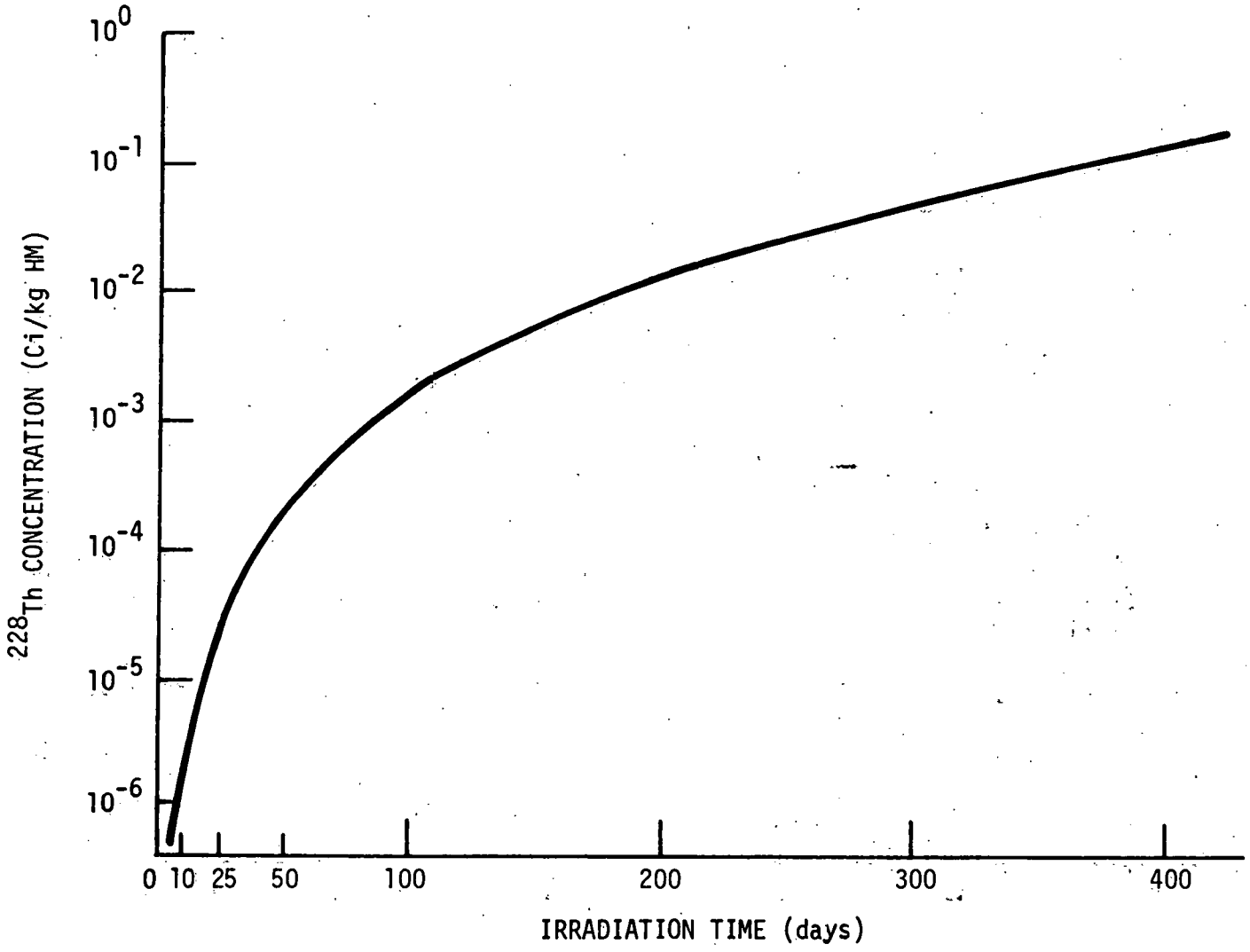

Figure 3-1. Concentration of ^{228}Th in Irradiated Thorium.

TABLE 3-2

BUILDUP OF THORIUM-228 IN A THORIUM HYBRID BLANKET

IRRADIATION TIME days	^{228}Th CONCENTRATION gm/MTHM	^{228}Th CONCENTRATION Ci/kg HM
0	0	0
10	2.22×10^{-6}	1.82×10^{-6}
25	3.45×10^{-5}	2.83×10^{-5}
50	2.74×10^{-4}	2.25×10^{-4}
100	2.16×10^{-3}	1.77×10^{-3}
200	1.69×10^{-2}	1.39×10^{-2}
400	1.29×10^{-1}	1.06×10^{-1}

The thorium-228 level immediately after separation of uranium and thorium is:

$$N_{08}' = N_{08} e^{-\lambda_{08} t'} + \frac{\lambda_{22} N_{22}}{\lambda_{22} - \lambda_{08}} (e^{-\lambda_{08} t'} - e^{-\lambda_{22} t'}) \qquad (3\text{-}4)$$

where t' is the time delay before reprocessing and N_{08} and N_{22} (given by Eqs. 3-2 and 3-3) are the thorium and uranium concentrations respectively immediately after the fuel is removed from the reactor.

If there is a delay before the thorium is recycled after reprocessing, the thorium-228 begins to decay away. The concentration remaining after a delay t'' is given by:

$$N_{08}''' = N_{08}'' e^{-\lambda_{08} t''} \qquad (3\text{-}5)$$

If the thorium is recycled several times the ^{228}Th concentration approaches an equilibrium concentration given by[2]:

$$N_{08}^{\infty} = \frac{N_{08}'}{1 - e^{-\lambda_{08} (t + t' + t'')}} \qquad (3\text{-}6)$$

where N_{08}' is the concentration after the first cycle.

Using Equations 3-3 through 3-6, one can compute the ^{228}Th levels at any time in the fuel cycle.

REFERENCES FOR SECTION 3.0

1. B. R. Leonard, Jr. and U. P. Jenquin, "The Quality of Fissile Fuel Bred in a Fusion Reactor Blanket," Presented at the Second Topical Meeting on: The Technology of Controlled Nuclear Fusion, September 21-23, 1976, Richland, Washington, Battelle Pacific Northwest Laboratories, BNWL-SA-5750, Richland Washington, 1976.

2. E. D. Arnold, "Radiation Hazards of Recycled ^{233}U Thorium Fuels," Proceedings of the Thorium Fuel Cycle Symposium, Gatlinburg, TN, December 5-7, 1962; United States Atomic Energy Commission Division of Technical Information TID-7650.

4.0 THE EFFECT OF RADIATION LEVELS ON FUEL FABRICATION COSTS

The effect of radiation levels on fuel fabrication costs has been studied by the Nuclear Fuels Division of Westinghouse Electric Corporation[1]. The incremental capital and operating costs expected to be incurred in a light-water reactor mixed-oxide fuel fabrication plant as a result of spiking the nuclear fuel with various levels of radioactive materials, including ^{228}Th, are estimated.

Economic results are given in two forms as capital and operating costs and as dollars per kilogram heavy metal processed. The latter is found by a discounted cash flow analysis over a ten year payback period resulting in an internal rate of return of 25%. The plant is designed to process 200 metric tonnes of mixed-oxide fuel per year. The results are given in 1975 dollars.

The mixed-oxide fuel contains 6% PuO_2 and 94% UO_2 where only the PuO_2 is spiked. An adjustment has been made to account for 100% of thorium fuel irradiated in a hybrid being contaminated by multiplying the radiation level at which each cost would be incurred by 0.06.

The results in terms of $/kg are presented in Figure 4-1. The operating and capital costs are given in Tables 4-1 and 4-2. A rough estimate of the uncertainty in the cost estimates is given as 30-50%.

REFERENCES FOR SECTION 4.0

1. R. F. Duda, "Study of the Cost Impacts of Spiking Plutonium," Westinghouse Nuclear Fuel Division, Pittsburgh PA (1975).

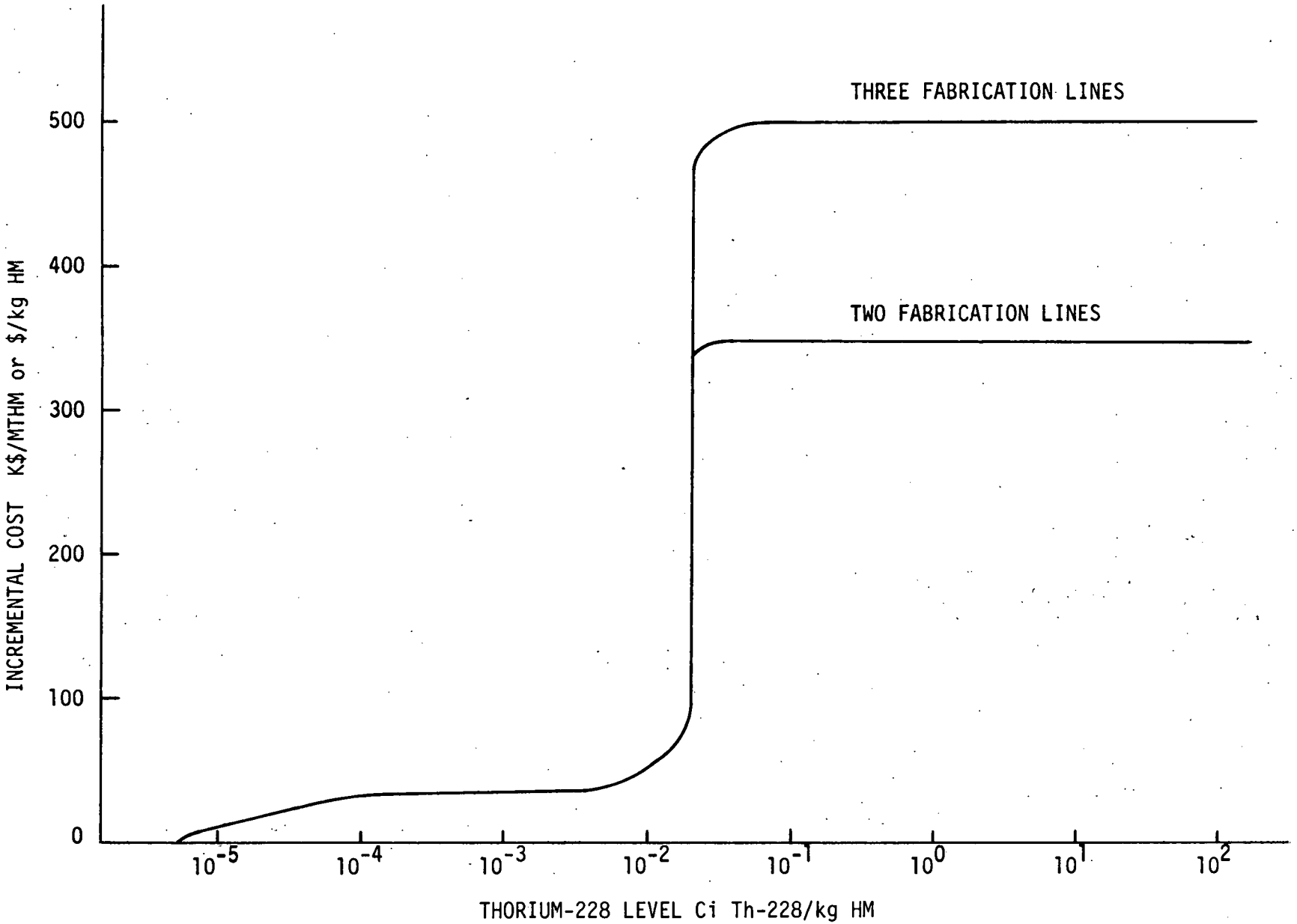

Figure 4-1. Effect of Thorium-228 Level on Incremental Fuel Fabrication Cost (1975$).

TABLE 4-1

INCREMENTAL OPERATING COSTS ($K/yr, 1975$)

(200 metric tonnes of ThO_2/year capacity)

	SPIKING LEVEL (Ci/kg ThO_2)											
	$6x10^{-5}$	$6x10^{-5}$	$6x10^{-4}$	$6x10^{-3}$	6×10^{-2}		6×10^{-1}		6		60	
COSTS	2 LINE	2 LINE	2 LINE	2 LINE	2 LINE	3 LINE	2 LINE	3 LINE	2 LINE	3 LINE	2 LINE	3 LINE
PLANT PERSONNEL	22	142	301	341	939	1900	939	1900	939	1900	939	1900
FACTORY EXPENSE		477	484	491	1020	1064	1020	1064	1020	1064	1020	1064
HEALTH PHYSICS SERVICES	122	122	122	122	122	122	122	122	122	122	122	122
TOTAL	144	741	907	954	2081	3086	2081	3086	2081	3086	2081	3086

← REMOTE PLANT →

TABLE 4-2

INCREMENTAL CAPITAL COSTS ($K, 1975$)

(200 metric tonnes of ThO_2/year capacity)

	SPIKING LEVEL (Ci/kg ThO_2)											
	$6x10^{-6}$	$6x10^{-5}$	$6x10^{-4}$	$6x10^{-3}$	6×10^{-2}		6×10^{-1}		6		60	
COSTS	2 LINE	2 LINE	2 LINE	2 LINE	2 LINE	3 LINE	2 LINE	3 LINE	2 LINE	3 LINE	2 LINE	3 LINE
GENERIC	945	945	945	945	5570	5570	5570	5570	5570	5570	5570	5570
SHIELDING		130	750	1900								
STRUCTURAL		70	400	990								
REMOTE SYSTEMS		9400	9650	10000								
LARGER BLDG.		930	930	930	142000	213000	142000	213000	142000	213000	142000	213000
TOTAL	945	11475	12675	14765	147570	218570	147570	218570	147570	218570	147570	218570

← REMOTE PLANT →

5.0 ECONOMIC ANALYSIS

5.1 IDENTIFICATION OF ALTERNATIVES

The presence of high levels of radioactivity in hybrid irradiated thorium as shown in Section 3 and the high cost penalty associated with remote fuel fabrication necessitated by these high radiation levels raises the possibility that it may not be economical to directly recycle thorium in the hybrid. Methods of replacing fuel other than direct recycle are identified in this section.

5.1.1 SHORT IRRADIATION TIME

The amount of radioactivity in hybrid irradiated thorium grows with irradiation time as shown in Section 3. This opens up the possibility of avoiding expensive remote fuel fabrication facilities by shortening the fuel residence time in the hybrid.

There is a steep jump in the cost of fuel fabrication at a thorium 228 concentration between 10^{-2} and 10^{-1} curies per kilogram heavy metal (see Figure 4-1). This concentration is achieved in less than 400 days as shown by Figure 3-1. Thus, this alternative requires the irradiation period to be shortened to less than 400 days.

Since the dominant costs associated with refueling, the cost of fabricating new fuel elements, and the cost of downtime are inversely proportional to the fuel residence time in the reactor it has proved economical to maximize the fuel residence time to the lifetime of the fuel elements, a period of three years or longer. To decrease the fuel residence time would impose a cost penalty of $\$3 \times 10^5$, the approximate cost of fabricating a tonne of fuel in a hands-on facility, per extra tonne of thorium processed while the economic gain is according to Figure 4-1 up to $\$5 \times 10^5$ per metric tonne processed. It is estimated approximately 14 tonnes per year are recycled through the hybrid

(see Figure A-1) when the residence time is three years. There would be three times as much or 42 tonnes per year if the irradiation time were cut to one year. In the case of a three year residence time the cost would be ($3 x 10^5 + $5 x 10^5/tonne) x 14 tonnes or $112 x 10^5 while in the case of one year residence time the cost would be $3 x 10^5 per tonne x 42 tonnes or $126 x 10^5. The added costs of having to reprocess three times as much fuel and to keep a fuel inventory three times as large make the short irradiation time option even more economically unfeasible.

5.1.2 WINDOW

There is a window in time where thorium is less radioactive immediately after reprocessing since reprocessing removes radioactive decay daughters. One alternative is to fabricate using this window before radioactive thorium 228 decay products build up to levels that require remote fuel fabricating facilities. The build up of thorium 228 daughters is indicated in Figure 5-1. The build up is controlled by the ^{224}Ra decay time of 3.4 days (see Figure 2-2). The time allowed to complete fuel fabrication depends on how fast radioactivity builds up and how much radioactivity is left behind on each cycle.

Fuel fabrication in conventional processes[1] can be finished 16 days from separation. There is a delay of about 2-3 days to concentrate fuel after solvent extraction (the separation process). The sol-gel process where the fuel is converted to an oxide takes another 3.5-4.5 days so the fuel has aged about 7.5 days on the average before fuel fabrication even starts. This includes delays due to breakdown and those necessary to insure the fuel meets proper specifications. A very optimistic estimate[2] for a continuous type of operation gives at least two days for delay from separation to finished fabrication.

After about two days the radioactivity levels have risen to 30% of equilibrium (see Figure 5-1). From Figure 3-1 one can see if a conventional fuel residence time is used (three years or longer) 30% of equilibrium will put the radiation levels over the hands-on fabrication limit of between 10^{-2} and 10^{-1} curies per kilogram of heavy metal.

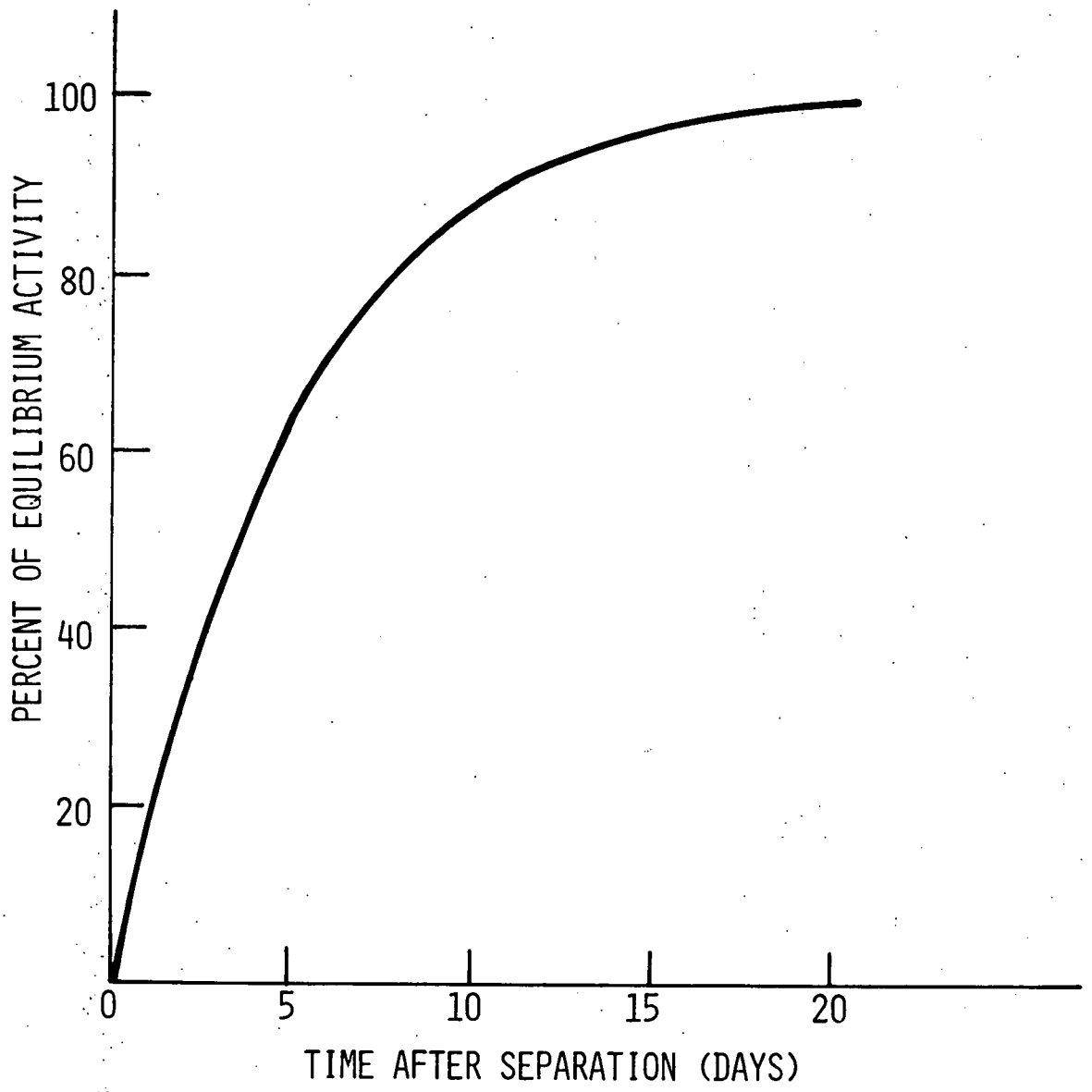

Figure 5-1. Growth of ^{208}Tl Gamma Activity as a Function of Post Purification Time.

5.1.3 STORAGE

The radiation levels in hybrid irradiated thorium will gradually decrease with time as the radioactive components decay out. The rate of this decrease is controlled by the 1.91 year half-life of ^{228}Th (see Figure 2-3). From Figure 3-1 it is estimated that the ^{228}Th concentration will be about 100 times the maximum permissible for hands-on fuel fabrication to be feasible. To decrease levels by a factor of 100 would require at least seven half-lives or approximately 14 years. The cost of storing radioactive thorium for this 14 years and the cost of the added inventory of thorium needed to make this alternative possible are the major cost penalties incurred in this option.

5.1.4 THROWAWAY

In this option the hybrid irradiated thorium is treated as waste. Since the thorium contains a low level emitter ^{230}Th it will be necessary to provide permanent storage such as in a geologic storage site. Costs for treating and disposal of the thorium are taken to be the same as those expected for waste arising from reprocessing such as fission products. Another important cost incurred in this alternative is the cost of purchasing new thorium. The costs of purchasing new thorium and disposing of the old will have to be less than the extra cost of remote fuel fabrication for this option to be desirable.

5.1.5 CONCLUSIONS

The option of shortening the irradiation time is not feasible. The option of using a window does not eliminate the need for expensive remote fuel fabrication processes; however, this option reduces radiation levels at little cost so it may prove useful in conjunction with another option. The remaining options, storage and throwaway, will be examined in more detail together with the direct recycle option to see if either of the three has clear economic superiority over the other two.

5.2 ECONOMIC ASSUMPTIONS

As a basis for further economic analysis of the three options: storage, throw-away, and direct recycle, identified in the preceeding section, the set of economic assumptions that have been used are listed below.

- The planning horizon, the time period over which costs are being calculated, is chosen to be 30 years or the approximate useful lifetime of a fuel fabrication facility.
- An interest rate of 16% per year is chosen to represent the time value of money.
- An equilibrium economy of 200 gigawatts of electric consumption is assumed. Start-up costs prior to equilibrium have not been considered.
- Material flows for the 200 GW(e) economy are calculated from Figure A-1 indicating 42 hybrids (CTHR's) and 188 PWR's will be necessary with 2756 tonnes of thorium recycled each year.
- All cost information has been adjusted to 1980 dollars by the following method. If r is the rate of inflation, 10% per year is assumed, and m is the number of years over which inflation has occurred, four years for example if costs were given initially in 1976 dollars, then a factor $I_f = (1 + r)^m$ is used to escalate the cost. For example, I_f x 1976 \$ = 1980 \$, where $I_f = (1 + 0.10)^4$.
- Most costs in the literature are given as lump sum capital costs and operating costs. In order to develop cash profiles the capital costs are assumed to be distributed equally over the three years prior to the beginning of operation.

5.3 COST CALCULATIONS

5.3.1 HOW COSTS ARE CALCULATED

All cost comparisons have been performed in terms of mills/kW-hr in order to readily show how different alternatives affect the cost of electricity. Costs have been converted to annual worth values and information on material flows and energy production given in Appendix A is used in the following equations to get operating and capital costs in terms of mills/kW-hr.

$$\text{CAPITAL COST}\left[\frac{\text{mills}}{\text{kW-hr}}\right] = \frac{I_f \dfrac{S_c[\$]D}{T\left[\frac{MT}{yr}\right]}\, O_h\,[\text{MT/GW(e) yr}]\; 1000\left[\frac{\text{mills}}{\$}\right] \frac{A}{P}\,[yr^{-1}]}{8.85125 \times 10^9\,[\text{kW-hr/GW(e)-yr}]} \qquad (5\text{-}1)$$

$$\text{OPERATING COST}\left[\frac{\text{mills}}{\text{kW-hr}}\right] = \frac{I_f \dfrac{S_o[\$/yr]}{T\left[\frac{MT}{yr}\right]}\, O_h\,[\text{MT/GW(e) yr}]\; 1000\left[\frac{\text{mills}}{\$}\right]}{8.85125 \times 10^9\,[\text{kW-hr/GW(e)-yr}]} \qquad (5\text{-}2)$$

where S_c = capital cost for a plant of capacity of T tonnes/yr

S_o = operating cost on an annual basis

O_h = tonnes of thorium produced per GW(e)-yr available for recycle [note 1 GW(e)-yr = 8.85125×10^9 kW-hr]

I_f = inflation factor to convert dollars to base year (1980)

$I_f = (1 + r)^m$ r = inflation rate (10%)
m = number of years of inflation

$\frac{A}{P}$ = factor used to convert one time investment (P) to a yearly cash flow (A)

$$\frac{A}{P} = \frac{i\,(1 + i)^n}{(1 + i)^n - 1}$$

where i = expected rate of return on investments (16%)

n = plant lifetime

D = factor which accounts for the equal distribution of capital costs over three years prior to start up

$$D = \frac{1}{3}\left[\frac{(1 + i)^3 - 1}{i}\right]$$

5.3.2 FUEL FABRICATION COSTS

The direct recycle option will require fuel fabrication facilities that can handle highly radioactive fuel. The extra costs incurred due to the high radioactivity of the fuel are discussed in Section 4.0. Those costs are presented again in Table 5-1 together with costs from various additional sources for comparison.

Using the capital and operating costs given by Duda (see Table 5-1) and Equations (5-1) and (5-2) gives the incremental fuel cycle costs due to radioactivity in fuel fabrication as shown below:

$$\text{CAPITAL COST}\ \left[\frac{\text{mills}}{\text{kW-hr}}\right] = \left\{(1 + 0.10)^5\ \frac{218.570 \times 10^6}{200}\left(\frac{1}{3}\left[\frac{(1 + 0.16)^3 - 1}{0.16}\right]\right)\right\} \times \left\{\frac{(13.78)\ (1000)\ \frac{0.16\ (1 + 0.16)^{30}}{(1 + 0.16)^{30} - 1}}{8.85125 \times 10^9}\right\} \qquad (5\text{-}3)$$

$$= 0.518\ \text{mills/kW-hr}$$

$$\text{OPERATING COST}\ \frac{\text{mills}}{\text{kW-hr}} = \frac{(1 + 0.10)^5\ \frac{3.086 \times 10^6}{200}\ (13.78)\ 1000}{8.85125 \times 10^9} \qquad (5\text{-}4)$$

$$= 0.0387\ \text{mills/kW-hr}$$

5.3.3 INVENTORY COSTS

The recycle after storage option will require a much greater inventory of thorium than the direct recycle and throwaway options will require. As indicated in Section 5.3, irradiated thorium would have to be stored at least 14 years to allow radioactivity to decay to levels where hands-on fuel fabrication would be feasible.

After equilibrium there would be an inventory in storage of 14 years x 13.78 tonnes thorium recycled/GW(e)-yr = 192.92 tonnes/GW(e)-yr.

TABLE 5-1

FUEL FABRICATION COSTS

SOURCE	CAPITAL * COST $ x 10^6	OPERATING * COST $ x 10^6	CAPACITY tonnes/yr	YEAR	LOW RADIOACTIVITY FABRICATION COSTS $/kg	HIGH RADIOACTIVITY FABRICATION COSTS $/kg	INCREMENTAL COST DUE TO RADIOACTIVITY $/kg	COMMENTS
RNFCC (3)	NA†	NA	60	1976	378 ± 120	NA	NA	MOX Fuel Fabrication Facility Amortized Over 15 Years with 10%/year Interest Charges
	75	12	75		NA	NA	NA	
	165	26	200		NA	NA	NA	
	NA	NA	300		226 ± 90	NA	NA	
	290	42	400		NA	NA	NA	
	510	74	800		NA	NA	NA	
DUDA (4)								
2 LINE	[142]	[2.081]	200	1975	250 - 300	600 - 650	350	MOX Fuel (Pu-U); Incremental Cost Calculated Using a 10 Year Discounted Cash Flow With a 25% Rate of Return; Uncertainty 30-50%
3 LINE	[213]	[3.086]	200		250 - 300	750 - 800	500	
KASTEN (5)	NA	NA	130	1977	306	780.3	474.3	Cost Calculated Using a 30% Capital Fixed Charge Rate; LWR Fuel-Low Radioactivity Fuel is U-235 and Unrecycled Thorium, High-Radioactivity is Pu and Recycled Th; Costs are Accurate to ± 25%
	NA	NA	260		246	627.3	381.3	
	NA	NA	520		200	510	310	
	NA	NA	1040		180	459	279	
	NA	NA	1560		168	428.4	260.4	
	NA	NA	2080		158	402.3	244.3	
BROOKSBANK (6)	NA	NA	15.6	1964	211	243	32	22% Amortization; SSCR Fuel-Low Radioactivity Fuel is U-235 and Virgin Thorium, High-Radioactivity Fuel is U-233 and Recycled Thorium
	NA	NA	59.8		100	112	12	
	NA	NA	241.8		55	60	5	
	NA	NA	962		36	39	3	

*The brackets in these columns [] indicate the changes are only incremental charges due to high radioactivity levels

†NA indicates "not available" in that report

Assuming thorium costs \$40/kg this inventory represents a capital investment of 192.92 tonnes/GW(e)-yr x \$40/kg x 1000 kg/tonne = \$7.7168 x 10^6/GW(e)-yr. This capital is paid out over a total of 14 years in annual increments of 13.78 tonnes/GW(e)-yr x \$40/kg x 1000 kg/tonne = \$5.51 x 10^5/GW(e)-yr. Converting these annual investments to the present worth at the beginning of the 14 years requires a factor $P/A = [(1 + i)^n - 1]/i(1 + i)^n$ where n in this case is 14 years. An equation similar to (5-1) then gives the levelized cost over the 30 year planning horizon of this study.

INVENTORY COST =

$$\frac{\frac{(1 + 0.16)^{14} - 1}{0.16\,(1+0.16)^{14}} \times \$5.51 \times 10^5 \left[\text{GW(e)-yr}\right]^{-1} \times 1000 \left[\frac{\text{mills}}{\$}\right] \frac{0.16\,(1+0.16)^{30}}{(1 + 0.16)^{30} - 1}}{8.85125 \times 10^9 \left[\frac{\text{kW-hr}}{\text{GW(e)-yr}}\right]}$$

$$\text{INVENTORY COST} = 0.055 \frac{\text{mills}}{\text{kW-hr}}$$

It should be noted that this cost is written off in the first cycle after equilibrium after which it is never incurred again, unlike capital costs for a storage facility for example since the storage facility would wear out and have to be replaced.

5.3.4 THORIUM MAKE-UP COSTS

The throwaway option requires a cost to replace used thorium called the make-up cost which is much greater than in the direct recycle and recycle after storage options. All options according to Figure A-1 in Appendix A require 2.077 tonnes of thorium per GW(e)-yr while the throwaway option requires an additional 13.78 tonnes of thorium which is recycled in the other two options. Replacement of this 13.78 tonnes entails a make-up cost of \$40/kg x 1000 kg/tonne x 13.78 tonnes/GW(e)-yr = \$5.51 x 10^5 per GW(e)-yr where it is assumed thorium costs \$40/kg.

In terms of mills/kW-hr, this represents a fuel cycle cost of

$$\frac{\$5.513 \times 10^5 \left[\frac{}{\text{GW(e)-yr}}\right] \times 1000 \left[\frac{\text{mills}}{\$}\right]}{8.85125 \times 10^9 \text{ [kW-hr/GW(e)-yr]}} = 0.0623 \frac{\text{mills}}{\text{kW-hr}}$$

5.3.5 STORAGE COSTS

In the recycle after storage option unreprocessed thorium is stored for approximately 14 years to allow its radioactivity to decrease to levels where hands-on fuel fabrication can be performed. Thorium could be stored as spent fuel elements or, if the fuel is reprocessed, thorium would be stored as a nitrate, oxide, or metal. Storage as thorium nitrate solution has been chosen in the following analysis since it is advantageous to reprocess as early as possible to recover valuable ^{233}U and since a thorium nitrate solution can easily be reprocessed again after the 14 year storage period to remove impurities that will have built up.

Storage Capacity Requirements

According to Appendix Figure A-1, 13.78 tonnes of irradiated thorium are generated for recycle in the hybrid per GW(e)-yr of electrical production. This will have to be stored for 14 years before recycle resulting in a total equilibrium accumulation of 13.78 x 14 = 193 tonnes/GW(e)-yr. Assuming a thorium concentration of 400 gms per liter the storage capacity required is

$$\frac{1}{400} \left[\frac{\text{gm}}{\ell}\right] \times 10^6 \frac{\text{gm}}{\text{tonne}} \times 193 \left[\frac{\text{tonnes}}{\text{GW(e)-yr}}\right] = 4.825 \times 10^5 \text{ liters per GW(e)-yr}$$

Costs for Storage as Nitrate Solution

Costs for storage of thorium nitrate solutions are assumed to be similar to costs for storage of neutral liquid radioactive waste. These costs are summarized in Table 5-2. The total capital cost in mills/kW-hr for storing 14

TABLE 5-2

CAPITAL COSTS OF WASTE STORAGE TANKS (NEUTRAL WASTE)

SOURCE	CAPACITY [m^3]	YEAR	MATERIAL	INTERNAL COOLING	REFLUX	TOTAL COST($)	COST/m^3($)	COMMENT
LONG[7]	2,271	1954	CARBON STEEL	YES	YES	1,080,000	475.5	
	3,785	1955	CARBON STEEL CONCRETE	NO	YES	403,000	105.7	
	113	1952	STAINLESS STEEL LINER	NO		83,090	731.7	
RNFCC[8]	1,125	1976				15,000,000	13,333	HIGH-LEVEL WASTE
	750	1976				12,000,000	16,000	HIGH-LEVEL WASTE
	562.5	1976				10,000,000	17,778	HIGH-LEVEL WASTE
	1,000	1976				1,500,000	1,500	MEDIUM-LEVEL WASTE

years of hybrid thorium output as spent fuel is calculated below assuming capital charges of $\$1500/m^3$ (see Table 5-2)

$$\text{CAPITAL COST} = \frac{(1 + 0.10)^4 \ \$1500\ [m^3]^{-1}\ \frac{482.5\ [m^3]}{[GW(e)\text{-}yr]}\ 1000\ [\frac{mills}{\$}]\ \frac{0.16\ (1 + 0.16)^{30}}{(1 + 0.16)^{30} - 1}}{8.85125 \times 10^9\ [kW\text{-}hr/GW(e)\text{-}yr]}$$

CAPITAL COST = 0.0194 mills/kW-hr

Cost information on operating costs was not available in the sources used for obtaining capital costs. They are, however, small compared to the capital costs.

TABLE 5-3[9]

SPENT FUEL STORAGE COSTS

CAPACITY TONNES	CAPITAL COST $ x 10^6	RECEIPT RATE TONNES HM/yr	OPERATING COST $ x 10^6
300	20 - 40	300	4
750	30 - 60	1500	6
1000	40 - 80	3000	7
2000	70 - 140		
3000	100 - 200		
4000	120 - 240		
5000	140 - 280		

For comparison, costs for storing the thorium as spent fuel elements are also calculated.

Costs for Storage As Spent Fuel

The total capital cost in mills/kW-hr for storing 14 years of hybrid thorium output as spent fuel is calculated using costs for the largest capacity storage facility given in Table 5-3.

$$\text{CAPITAL COST} = \frac{(1 + 0.10)^4 \; \frac{\$140 \times 10^6}{5000 \text{ tonne}} \times \frac{193 \text{ tonnes}}{\text{GW(e)-yr}} \; \frac{1}{3} \; \frac{(1 + 0.16)^3 - 1}{0.16} \times \frac{1000 \text{ mills}}{\$} \times \frac{0.16 \; (1 + 0.16)^{30}}{(1 + 0.16)^{30} - 1}}{8.85125 \times 10^9 \; [\text{kW-hr/GW(e)-yr}]}$$

$$\text{CAPITAL COST} = 0.169 \; \frac{\text{mills}}{\text{kW-hr}}$$

The capital cost will vary with the reactivity of the fuel as this determines how close together fuel bundles may be packed. Also, the capital costs in Table 5-3 are for short-term storage prior to reprocessing. For these reasons the actual cost of storing thorium as spent fuel might easily be half as much as the value calculated above. The total operating cost in mills/kW-hr is calculated using the figure for the largest receipt rate given in Table 5-3, 3000 tonnes/yr.

$$\text{OPERATING COST} = \frac{(1 + 0.10)^4 \; \frac{\$ \; 7 \times 10^6}{3000 \text{ tonne}} \times 13.78 \; \frac{\text{tonnes}}{\text{GW(e)-yr}} \times 1000 \; \frac{\text{mills}}{\$}}{8.85125 \times 10^9 \; [\text{kW-hr/GW(e)-yr}]}$$

$$= 0.0053 \; \frac{\text{mills}}{\text{kW-hr}}$$

5.3.6 WASTE DISPOSAL COSTS

The cost of waste disposal is incurred in the throwaway option where 13.782 tonnes of thorium must be disposed of for every GW-hr of electricity produced. Disposal costs include mainly costs for incorporating the waste in a stable solid substance such as glass or bitumin and costs for storing the waste in a geologic storage site. Geologic storage is necessary because of substancial radiation levels due to ^{230}Th[10]. Costs for various solidification processed are given in Table 5-4.

TABLE 5-4[11]

A) HIGH LEVEL WASTE SOLIDIFICATION INTO GLASS

$\$ \times 10^6$	AMOUNT m^3
200	750
120	375
80	187.5
40	75
24	32.5

B) MEDIUM LEVEL WASTE SOLIDIFICATION
(INCORPORATION INTO BITUMINOUS MATRIX)

$\$ \times 10^6$	AMOUNT m^3	VOLUME REDUCTION
42	15,000	3 - 5
26	7,500	
14	3,750	
7	1,500	
4	750	

In a typical[12] geologic storage site high level waste (HLW) is stored in small pits spaced to allow for heat dissipation in horizontal access tunnels. These tunnels represent about 300 m^3 of unused storage space for each m^3 of high level waste stored which is enough capacity to store all the thorium. Because no special facility has to be built the costs for geologic storage of the thorium are negligible.

The thorium is assumed to be treated as medium level waste*. If the amount of fuel discarded (from the Appendix Figure 1), 13.78 tonnes/GW(e)-yr, is at a concentration of 400 gm/ℓ the volume of thorium waste per GW(e)-yr is given by

$$\frac{13.78 \times 10^6 \text{ gms/Gw(e)yr}}{400 \text{ gms/ℓ}} \times \frac{1}{10^3 \text{ liters/m}^3} = 34.45 \text{ m}^3\text{/GW(e)-hr}$$

The capital cost for incorporation of thorium into a bituminous matrix is calculated using costs from Table 5-4 B.

$$\text{CAPITAL COST} = \frac{(1 + 0.10)^4 \frac{\$26 \times 10^6}{7500 \text{ m}^3} \times 34.45 \frac{\text{m}^3}{\text{GW(e)-yr}} \times \frac{1}{3} \frac{(1 + 0.16)^3 - 1}{0.16}}{8.85125 \times 10^9 \text{ [kW-hr/GW(e)-yr]}} \times$$

$$\frac{1000 \frac{\text{mills}}{\$} \times \frac{0.16 (1 + 0.16)^{30}}{(1 + 0.16)^{30} - 1}}{8.85125 \times 10^9 \text{ [kW-hr/GW(e)-yr]}} = 0.00374 \text{ mills/kW-hr}$$

*Medium level waste is mainly a sodium nitrate solution with a 10-15% solid content and a radiation level os <1 ci/ℓ.

5.4 COMPARATIVE COST ANALYSIS & CONCLUSIONS (See Also 5.1.5)

Costs of the three options are compared in Table 5-5

The recycle after storage option is recommended. The major portion of cost building an inventory occurs only in the initial cycle and will not be in any equilibrium cycle. Even with this cost the recycle after storage option is much less than the direct fabrication option and approximately the same as the throwaway option. After inventory has been built up in the first cycle it will clearly cost much less than the throw away cycle. The cost penalty associated with the radioactivity of the thorium using the recycle after storage option is 0.0744 mills/kW-hr which represents an economic impact of 4×10^9 dollars over a 30 year period assuming 200 gigawatt supply of electrical power.

Transportation and associated costs were not discussed. The direct recycle option requires no special transportation over the other two cases. Assuming storage in the recycle after storage option would take place at the reprocessing facility itself. These transport cost can be neglected for the purpose of this study. The throwaway option most likely will have the greatest transportation requirements since it is likely that geologic disposal sites would not be at the reprocessing facilities and this makes the recycle after storage option even more favorable comparitively.

Interest Rates

The interest rate determines how important capital costs are in determining the final electricity costs. High interest rates penalize options with high capital costs. The capital costs are a significant share of all the options and increasing the interest rate will only magnify the difference between the options.

TABLE 5-5
COMPARATIVE COST ANALYSIS
(Costs in mills/kW-hr)

	DIRECT RECYCLE	RECYCLE AFTER STORAGE	THROW AWAY
FUEL FABRICATION (INCREMENTAL INCREASE FOR REMOTE)			
• CAPITAL	0.518	---	---
• OPERATING	0.0387	---	---
STORAGE COSTS			
• CAPITAL		0.0194 [0.169]†	
• OPERATING		NEGLECT [0.0053]	
THORIUM INVENTORY COST			
@ $40/kg	---	0.055*	
THORIUM MAKEUP COST	---	---	0.062
WASTE DISPOSAL COST (AS LOW LEVEL α WASTE DUE TO ^{230}Th)			
• CAPITAL			0.00374
• OPERATING			NEGLECT
TOTALS	0.5567	0.0744 [0.229]	0.06574

*This cost would be incurred only on the first cycle but not thereafter (see Section 5.4.3).

†Costs in brackets [] are for storage as spent fuel while the unbracketed costs are for storage as a nitrate solution (see Section 5.3.5).

Interest rates do not effect the conclusion choice of recycle after storage; however, they do effect the overall cost penalty associated with the thorium radioactivity.

Thorium Make Up Cost

An increase in thorium make-up cost of $40/kg would favor the recycle after storage option over the throwaway option. Thorium cost would have to increase by a factor of ~10 before the inventory costs for the recycle after storage option would approach the cost of direct recycle.

Technical Advances

The capital costs for direct recycle at the present are quite high because the technology for remote operations is not fully developed. As automation technology develops the capital costs for remote operation necessary in the direct recycle option may fall into a competitive range.

REFERENCES FOR SECTION 5.0

1. R. E. Broodsbank, J. P.. Nichols, and A. L. Lotts, "The Impact of Kilorod Facility Operational Experience on the Design of Fabrication Plants for ^{233}U-Th Fuels," Proceedings of the Second International Thorium Fuel Cycle Symposium, Gatlinburg, TN, May 3-6, 1966; AEC 12 Symposium Series, Thorium Fuel Cycles, Division of Technical Information (February 1968).

2 G. Schileo, "An Unshielded Pilot Plant for Recycling ^{233}U," Proceedings of the Second International Thorium Fuel Cycle Symposium, Gatlinburg, TN, May 3-6, 1966; AEC 12 Symposium Series, Thorium Fuel Cycle, Division of Technical Information (February 1968).

3. Regional Nuclear Fuel Cycle Centers, Vol II, Basic Studies 1977 Report of the IAEA Study Project, International Atomic Energy Agency, Vienna, 1977, STI/PUB/445 IBSN 92-0-159277-9, p. 275.

4. R. F. Duda, "Study of the Cost Impacts of Spiking Plutonium," Westinghouse Nuclear Fuel Division, Pittsburgh PA (1975).

5. P. R. Kasten, et al., "Assessment of the Thorium Fuel Cycle in Power Reactors," ORNL/TM-5565, January 1977.

6 R. E. Broodsbank, J. P.. Nichols, and A. L. Lotts, "The Impact of Kilorod Facility Operational Experience on the Design of Fabrication Plants for ^{233}U-Th Fuels," Proceedings of the Second International Thorium Fuel Cycle Symposium, Gatlinburg, TN, May 3-6, 1966; AEC 12 Symposium Series, Thorium Fuel Cycles, Division of Technical Information (February 1968).

7. J. T. Long, Engineering for Nuclear Fuel Reprocessing, Gordon and Breach Science Publishers Inc., New York, 1967, Chapter 14, pp 940.

8. Regional Nuclear Fuel Cycle Centers, Vol II, Basic Studies 1977 Report of the IAEA Study Project, International Atomic Energy Agency, Vienna, 1977, STI/PUB/445 IBSN 92-0-159277-9, p. 205.

9. Regional Nuclear Fuel Cycle Centers, Vol II, Basic Studies 1977 Report of the IAEA Study Project, International Atomic Energy Agency, Vienna, 1977, STI/PUB/445 IBSN 92-0-159277-9, pp 129-130.

10. B. R. Leonard, Jr. and U. P. Jenquin, "The Quality of Fissile Fuel Bred in a Fusion Reactor Blanket," Presented at the Second Topical Meeting on: The Technology of Controlled Nuclear Fusion, September 21-23, 1976, Richland, Washington, Battelle Pacific Northwest Laboratories, BNWL-SA-5750, Richland WA, 1976.

11. Regional Nuclear Fuel Cycle Centers, Vol II, Basic Studies 1977 Report of the IAEA Study Project, International Atomic Energy Agency, Vienna, 1977, STI/PUB/445 IBSN 92-0-159277-9, p 205.

12. Regional Nuclear Fuel Cycle Centers, Vol II, Basic Studies 1977 Report of the IAEA Study Project, International Atomic Energy Agency, Vienna, 1977, STI/PUB/445 IBSN 92-0-159277-9, pp 210-214.

APPENDIX A

MASS-ENERGY CALCULATIONS FOR A FISSION-FUSION HYBRID AND PWR SYMBIOTIC SYSTEM

The number of PWR's supported by one hybrid is given by

$$R = O_H/M \tag{1}$$

where O_H is the unreprocessed fissile output per year of the hybrid and M is the unreprocessed fissile make-up required per year by a PWR. The make-up can be found by noting that the PWR output, O_p, plus the make-up, M, must equal the PWR input, I_p. Actually, the following equation holds:

$$0.98\ (M + O_p) = I_p$$

where the factor 0.98 accounts for 1% loss of fissile material during reprocessing and 1% loss during fabrication. Solving for the make-up gives:

$$M = \frac{I_p}{0.98} - O_p \tag{2}$$

The number of PWR's, N_p, and the number of hybrids, N_H, in a symbiotic system producing 1000 MWe satisfy the following condition:

$$N_p E_p + N_H E_H = 1000\ \text{MWe} \tag{3}$$

where E_p and E_H are the average power generated by the PWR and hybrid, respectively. Using equation (3) and noting that $R = N_p/N_H$, the following equations for N_p and N_H can be derived:

$$\text{a)}\ N_p = \frac{1000\ \text{MWe}}{R \cdot E_p + E_H} \cdot R$$

$$\text{b)}\ N_H = \frac{1000\ \text{MWe}}{R \cdot E_p + E_H} \tag{4}$$

Table A-1 gives the basic parameters for the standard PWR assumed in the study and Table A-2 gives the basic parameters for the hybrid reactors. Table A-1 lists two cases, the "denatured" case where fissile ^{233}U produced by the hybrid is denatured with ^{238}U to make it less suitable for weapons manufacture and the

TABLE A-1

STANDARD PWR PARAMETERS[1]

CHEMICALLY SEPARABLE CASE

POWER		3817 MW(t)
		1276 MW(e)
HM INVENTORY		95.37 tonnes
TONNES OF ^{233}U	BOL	2.8690 tonnes
	EOL	1.9509 tonnes
FISSILE DESTROYED		3.5314 tonnes
FUEL RESIDENCE TIME		3 years
PLANT AVAILABILITY		80%

DENATURED CASE

POWER		3817 MW(t)
		1276 MW(e)
HM INVENTORY		98.22 tonnes
TONNES OF ^{233}U	BOL	3.2551 tonnes
	EOL	2.0182 tonnes
TONNES OF Pu	EOL	0.4068 tonnes
FISSILE DESTROYED		3.7730 tonnes
PLANT AVAILABILITY		80%

HM = Heavy Metal
BOL = Beginning-of-Life
EOL = End-of-Life

TABLE A-2

STANDARD HYBRID PARAMETERS[1]

DTHR

FUSION POWER	950 MW
AVERAGE PEAK THERMAL POWER	1973 MW(t)
CONVERSION EFFICIENCY	25%
NON-FISSION ENERGY ENHANCEMENT FACTOR	1.14
^{233}U PRODUCTION	538 kg in 3 years
AVERAGE % ^{233}U IN THORIUM	0.65%
PLANT AVAILABILITY x DUTY CYCLE	0.20
ENERGY CONSUMPTION	532 MW(e)

CTHR

FUSION POWER	950 MW
AVERAGE PEAK THERMAL POWER	3239 MW(t)
CONVERSION EFFICIENCY	25%
NON-FISSION ENERGY ENHANCEMENT FACTOR	1.14
^{233}U PRODUCTION	1300 kg in one year
AVERAGE % ^{233}U IN THORIUM	0.65%
PLANT AVAILABILITY x DUTY CYCLE	0.595
ENERGY CONSUMPTION	532 MW(e)

"chemically separable" case where nothing has been added to the fissile ^{233}U. Two hybrids, the DTHR and CTHR, have been described in Table A-2. The DTHR (Demonstration Tokamak Hybrid Reactor) is a first-step demonstration reactor, whereas the CTHR (Commercial Tokamak Hybrid Reactor) is an upgraded hybrid concept suitable for commercial use.

As an example, calculations will be performed for the case of a CTHR with the chemically separable fuel cycle.

From A-1

$$I_p = \frac{2.8690 \text{ tonnes of } ^{233}U \text{ at BOL}}{3 \text{ years}} = 0.9563 \text{ tonnes/year}$$

$$O_p = \frac{1.9509 \text{ tonnes of } ^{233}U \text{ at EOL}}{3 \text{ years}} = 0.6503 \text{ tonnes/year}$$

By Eq (2)

$$M = \left(\frac{0.9563 \text{ tonnes/year}}{0.98}\right) - 0.6503 \text{ tonnes/year} = 0.3255 \text{ tonnes/year}$$

From A-2

$$O_H = 1.300 \text{ tonnes/year}$$

By Eq (1)

$$R = \frac{O_H}{M} = \frac{1.300 \text{ tonnes/year}}{0.3255 \text{ tonnes/year}} = 3.99 \frac{\text{PWR's}}{\text{hybrid}}$$

Since

$$E_p = \text{electrical power x plant availability}$$

From A-1

$$E_p = 1276 \text{ MWe} \times 0.80 = 1020 \text{ MWe}$$

Also,

$$E_H = \{(\text{average peak thermal power} \times \text{conversion efficiency}) - \text{power consumption}\} \times \text{plant availability} \times \text{duty cycle.}$$

From A-2

$$E_H = \{(3239\ MW \times 0.25) - 532\ MWe\} \times 0.595$$

$$E_H = 165.3\ MWe$$

by Eq (4)

$$N_p = \frac{1000\ MWe}{3.99 \times 1020\ MWe + 165.3\ MWe} \times 3.99 = 0.94$$

$$N_H = \frac{1000\ MWe}{3.99 \times 1020\ MWe + 165.3\ MWe} = 0.24$$

Now, if any mass-energy parameter is known for the standard PWR and standard hybrid the value of that parameter can be found for a 1000 MWe symbiotic system by multiplying by the appropriate factor N_p or N_H.

Continuing with the example, the power contributed by the hybrid is $N_H \cdot E_H$ = 0.24 x 165.3 MWe = 40 MWe and the power contributed by the PWR is $N_p \cdot E_p$ = 0.94 x 1020 MWe = 960 MWe to make a total of 1000 MWe.

The heavy metal inventory of the PWR is from Table A-1 95.37 tonnes so the inventory for a 1000 MWe system is 95.37 x N_p = 89.65 tonnes.

The heavy metal inventory of the hybrid can be found from the following equation and Table A-2,

$$\text{HM inventory} = U \times (1 + \frac{1}{\varepsilon}) + FP + \text{Actinides}$$

where U is the ^{233}U production, ε is the average % ^{233}U in thorium, actinides is the amount of actinide produced which will be ignored, and FP is the amount of fission products produced.

The amount of fission products produced by the hybrid may be estimated using the following equation:

$$FP\ [\frac{\text{tonnes}}{\text{year}}] = \frac{P_{fission}\ [MW(t)] \times PA \times DC \times 365.25\ [\frac{\text{days}}{\text{year}}]}{0.95\ \frac{\text{MW days}}{\text{gm}} \times 10^6\ \frac{\text{gms}}{\text{tonne}}}$$

where PA x DC is the plant availability times the duty cycle given in Table A-2, 0.95 MW-days is the approximate energy released by the fissioning of one gram of ^{233}U, and $P_{fission}$ is the average fission power of the hybrid. $P_{fission} = \langle P_T \rangle - h \cdot P_F$ where $\langle P_T \rangle$ is the average peak thermal power, h is the non-fission energy enhancement factor, which accounts for non-fission exothermic reactions in the blanket, and P_F is the peak plasma fusion power.

From A-2

$$P_{fission} = 3239\ MW(t) - 1.14 \times 950\ MW(t)$$

$$P_{fission} = 2156\ MW(t)$$

and

$$FP = \frac{2156\ MW(t) \times 0.595 \times 365.25\ \frac{\text{days}}{\text{year}}}{0.95\ \frac{\text{MW days}}{\text{gm}} \times 10^6\ \frac{\text{gms}}{\text{tonne}}}$$

$$FP = 0.493\ \text{tonnes/year}$$

The heavy metal inventory for the hybrid is

$$\text{HM Inventory} = 1.300 \times (1 + \frac{1}{0.0065}) + 0.493\ \frac{\text{tonnes}}{\text{year}}$$

$$\text{HM inventory} = 201.79\ \text{tonnes}$$

The inventory for a 1000 MW(e) system is

$$N_H \times 201.79 = 48.430\ \text{tonnes.}$$

For CTHR calculations it is assumed that 1/3 of the blanket is removed every year containing 1300 kgs of fissile fuel. For the DTHR it is assumed that 1/3

of the blanket is removed every three years containing 538 kgs of ^{233}U. The results of these calculations are summarized in Figures A-1 through A-4.

REFERENCES FOR APPENDIX A

1. Anderson, et al., March 1978 Status Report on the Preliminary Conceptual Design of a Demonstration Tokamak Hybrid Reactor, Westinghouse Electric Corporation, WFPS-TME-086, June 1978. Section 4.2.3, especially Tables 4-23 and 4-24.

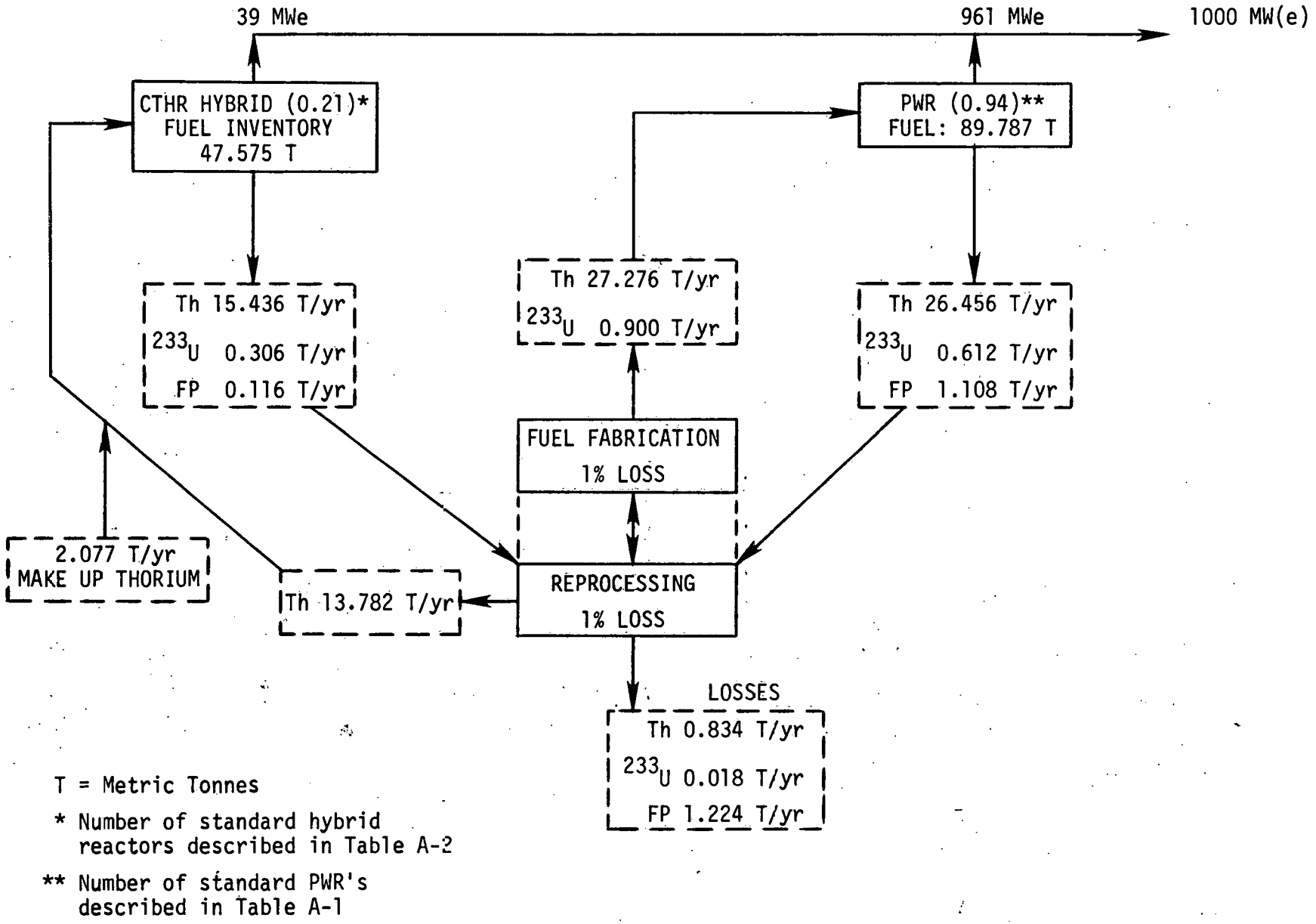

Figure A-1. Summary of Overall Mass/Energy Flows - Chemically Separable Fuel - CTHR.

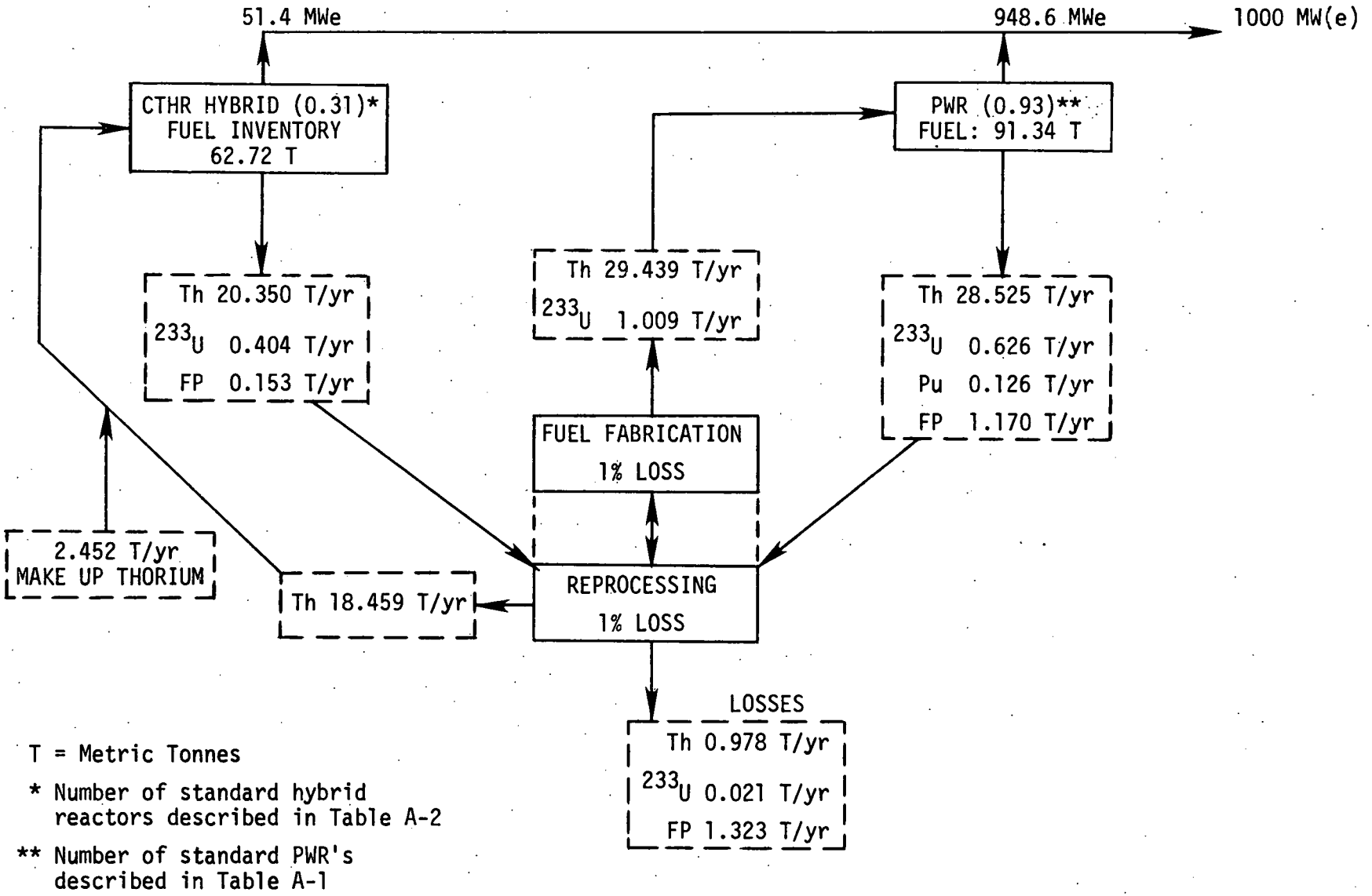

Figure A-2. Summary of Overall Mass/Energy Flows - Denatured Fuel - CTHR.

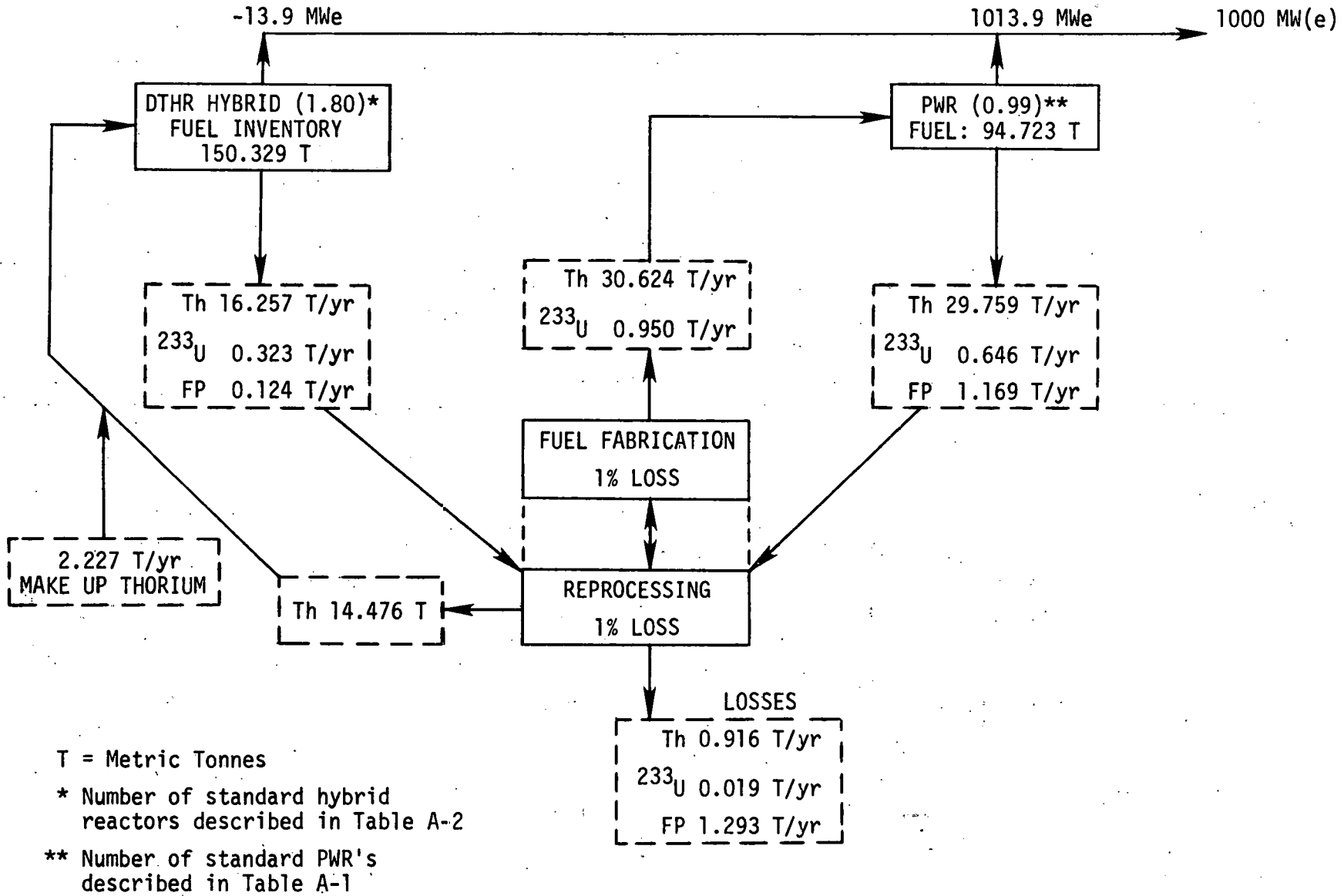

Figure A-3. Summary of Overall Mass/Energy Flows - Chemically Separable Fuel - DTHR.

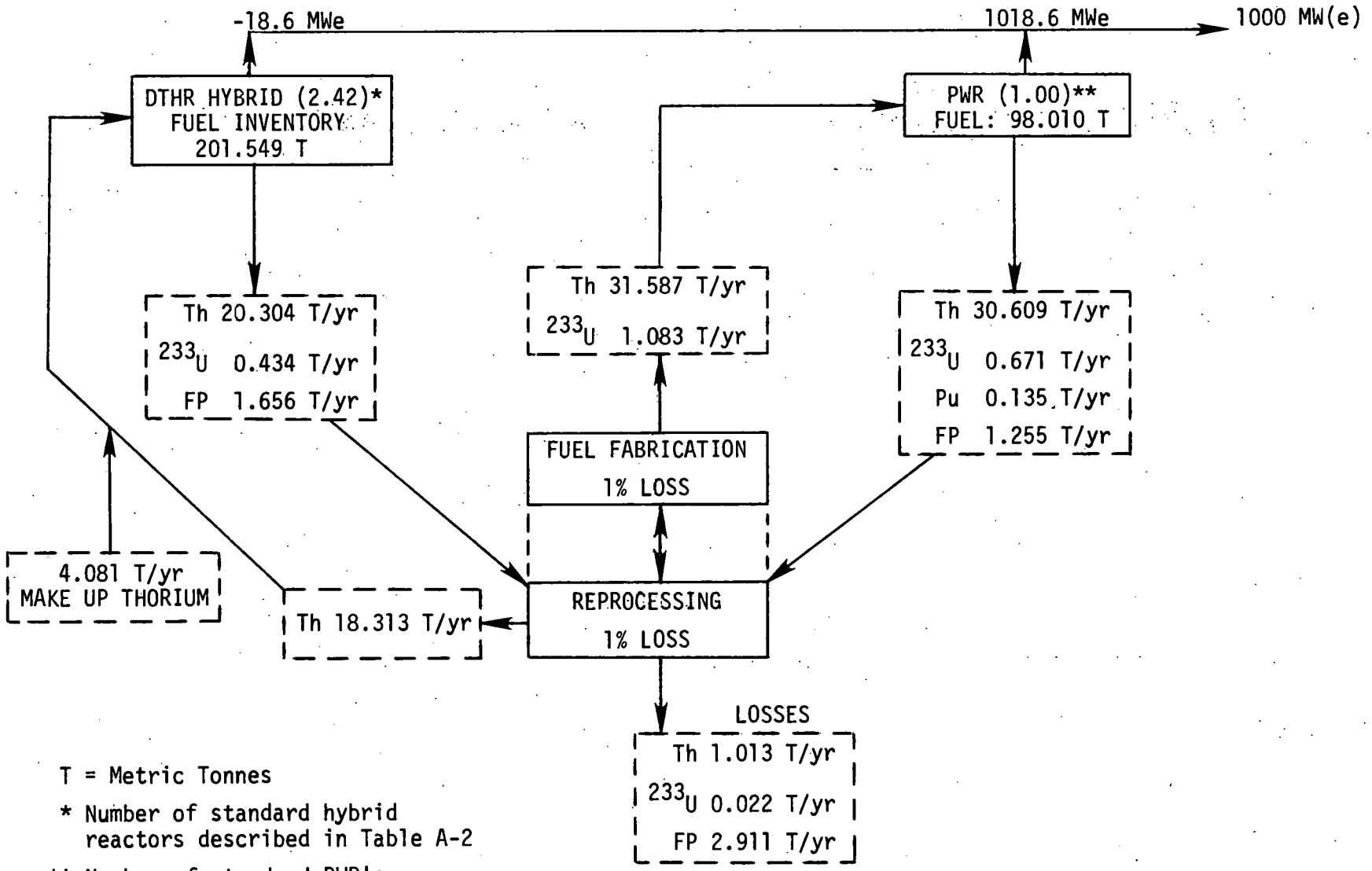

Figure A-4. Summary of Overall Mass/Energy Flows - Denatured Fuel - DTHR.

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