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EVALUATION OF DD AND DT FUSION FUEL CYCLES FOR DIFFERENT FUSION-FISSION ENERGY SYSTEMS

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ABSTRACT

A study has been carried out in order to investigate the characteristics of an energy system to produce a new source of fissile fuel for existing fission reactors. The denatured fuel cycles were used because it gives additional proliferation resistance compared to other fuel cycles. DT and DD fusion drivers were examined in this study with a thorium or uranium blanket for each fusion driver. Various fuel cycles were studied for light-water and heavy-water reactors. The cost of electricity for each energy system was calculated.

INTRODUCTION

Interest in fusion-fission hybrid energy systems has increased in the last few years. An important reason for this interest has been to develop new sources of fissile fuel to offset anticipated shortages of fissile material expected to occur at the end of this century.⁽¹⁻⁴⁾ This leads one to consider the fusion-fission hybrid reactor primarily as a fuel factory for producing fissile material. The production of fissile material from hybrid reactors would save the cost of enrichment process and it can use the existing piles of ^{238}U which reduces the cost of the entire fuel cycle. It may also provide more proliferation resistance by using denatured fuel cycles.^(1,5)

All these advantages can be maximized if the fusion-fission hybrid reactor can supply the fissile fuel to a large number of fission reactors. The purpose of this study was to evaluate the different energy systems, which consist of one fusion-fission hybrid reactor (fusion breeder) supplying fissile fuel for a number of fission reactors (fission burners). On the fusion breeder side of the energy system, DD or DT fusion fuel drivers were used for fissile production from uranium or thorium blankets. On the burner side of the energy system, two fission burners [the light-water reactor (LWR) and heavy-water reactor (HWR)] were considered with four different fission fuel cycles. The performance and cost of each system were calculated based on data from different sources.

HYBRID REACTOR

The hybrid reactor can be employed in two different modes of operation. One mode is a stand-alone energy production system where fissionable material is introduced in the blanket for energy multiplication. This mode of operation is generally viewed as unattractive⁽¹⁾ based on the current price of U_3O_8 , although it may be helpful if the first generation of fusion drivers

have low Q (Q is the ratio of fusion power to power injected into the fusion reactor).⁽²⁾ The other mode of operation is to view the hybrid reactor as a fuel factory for the other existing commercial fission reactors, mainly LWR and HWR reactors.

In this study, the analyses were performed for two different fusion reactors, the DD and DT fusion breeders. The DT fusion breeder requires a tritium breeding capability which could, in principal, be produced in the fusion reactor or fission burner reactors. Since DT fusion driver must have a tritium fueling and impurity purification system to maintain the plasma and large amounts of tritium would have to be shipped to the hybrid location if the tritium is generated away from the hybrid reactor, it is likely that the tritium will be produced in the hybrid reactor blanket. Also, the choice of breeding tritium in the fusion blanket may improve the safety of this energy system by minimizing tritium releases. DD was selected as an option in order to investigate the impact of not having to breed tritium in the energy system.

HYBRID BLANKET ASSUMPTION AND CONSIDERATIONS

Four blanket types have been considered for this study. The first two blankets have a tritium breeding capability for DT breeder reactors. Lithium oxide (Li_2O) was used for this study due to its high-lithium density and high-temperature capability. The other two blankets have no tritium breeding capability and are used for DD breeder reactors. Uranium-based and thorium-based fuel cycles were considered for both the DD and DT breeder options.

The coolant choice for this study was helium because it has the potential to increase the system thermal efficiency and lower the tritium inventory. In addition, helium does not moderate or absorb the neutrons and it has desirable safety features.

The choice of the structural material is dictated by the desire to improve the blanket performance and the thermal efficiency of the system. The blanket neutronic performance is sensitive to the amount of the structural material in the blanket and the first wall. This desire indicates a need for high-strength material to minimize the amount of structural material. Inconel 718 was selected in this study for the neutronic calculations.

The choice of fertile material for the hybrid blanket is influenced by a desire to have a high density in order to maximize the fuel breeding (neutron capture in the fertile material). The amount of structural material in the blanket should be low to minimize the structural parasitic absorption and spectral softening. Table I shows a list of important properties for different fuels. The choice for this study is uranium silicide (U_3Si) and thorium oxide (ThO_2). The motivations for the U_3Si choice are high uranium density, good thermal conductivity, high operating temperature compared to other metallic alloys, high burnup capability, and low irradiation swelling. The thorium oxide choice was motivated by its good performance under irradiation, cladding, compatibility, oxidation resistance, and high-temperature stability.

FISSION FUEL CYCLE CONSIDERATIONS

The hybrid reactor is viewed as a fuel factory which can utilize a uranium-based fuel cycle to produce ^{239}Pu or a thorium-based fuel cycle to produce ^{233}U . Under these fuel cycles, one can consider in-situ breeding without reprocessing and reprocessing concepts.

In in-situ breeding without reprocessing, conventional fission reactor fuel rods are enriched in a hybrid reactor and then used without reprocessing in a fission reactor. This option was investigated for breeding ^{233}U from thorium with 4% enrichment⁽³⁾ and then using this fuel in a fission reactor without reprocessing. The attraction of this cycle is obvious it does not require

TABLE I. Properties of Fuels

Fuel	Density (g/cm ³)	Metal Density (g/cm ³)	Thermal Conductivity cal/s-cm-°C	Melting Point (°C)
U	19.04	19.04	0.095	1133
U ₃ Si	16.1	15.5	0.05	930
UC	13.63	12.97	0.06	2400
UO ₂	10.96	9.66	0.007	2800
Th	11.7	11.7	0.1	1845
ThC	11.5	10.96	0.07	2625
ThO ₂	11.4	10.0	0.005	3300

reprocessing refabrication technology and it relaxes the nuclear proliferation issue, since the fissile material and the fission products will never be separated. In this concept the material limitations are of great concern because the cladding material must survive irradiation in both the fusion and fission reactors. The fast neutron fluence ($E > 0.1$ MeV) estimate for one enrichment-depletion cycle is 7.5×10^{22} n/cm²⁽³⁾ which is a challenge for the cladding material.

This study has considered only reprocessing concepts. Four different fuel cycles are employed in the analysis for a pressurized light-water reactor:

- a. Uranium cycle with full uranium, plutonium recycle and plutonium makeup from the hybrid reactor: In this fuel cycle both uranium and plutonium are recycled. This cycle shows a substantial reduction in overall demands on uranium resources.
- b. Thorium cycle with full thorium, ²³³U recycle and plutonium makeup from the hybrid reactor: The benefits of loading plutonium into thorium-based cycle is a higher conversion ratio and a lower fissile consumption per MWd relative to the uranium-based cycle.⁽⁴⁾
- c. Denatured uranium cycle with ²³³U makeup: In this cycle, ²³³U from the hybrid reactor is mixed with depleted uranium and the spent fuel is recycled except for the plutonium. The plutonium can be used in restricted fission reactors or in the hybrid reactor to improve the blanket performance.
- d. Denatured thorium cycle with ²³³U makeup: This cycle is similar to the denatured uranium cycle with ²³³U makeup, except thorium is used instead of uranium.

In general, the thorium-based fuel cycles require higher initial core loading to start the cycle⁽⁴⁾ than the uranium-based fuel cycles. The thorium cycles have higher conversion ratios and lower fissile consumption rates per

MWd. The denatured thorium with ^{233}U makeup has the uranium fuel cycle advantage of low initial core loading and the thorium fuel cycle advantages of high conversion ratio and low fissile consumption rates per MWd. This cycle is considered to be more proliferation-resistant than the other cycles.^(1,5) Fuel cycle parameters for the pressurized light-water reactor are listed in Table II. The data for the uranium cycles were taken from Ref. 4, while the data for the thorium cycles were taken from Ref. 5.

The denatured fuel cycle with ^{233}U makeup was used for heavy water reactors to take advantage of the low-neutron absorption in the moderator.⁽⁵⁾ The fuel cycle data is listed in Table II, where the savings in the annual net fissile requirements due to the use of heavy water is evident.

HYBRID BLANKET MODEL

Since the main objective of this study is to examine the hybrid reactor as a fuel factory, a neutronic scoping study was carried out to find a blanket configuration which maximizes the fissile production (^{233}U and ^{239}Pu). Table III shows the different blanket options used in this study. The first two blankets, A and B in Table III, are designed for the DT fusion breeder with tritium breeding capability. The fissile breeding zone thickness is varied from 5 to 25 cm to study the impact on the blanket performance. The tritium breeding zone is fixed at a 50-cm thickness since the neutron leakage from the blanket is less than 0.01 neutron per fusion neutron. The last two blankets, C and D in Table III, are designed for the DD fusion breeder where the blanket is used for breeding fissile material. In all the designs, a 1-cm first wall with 0.5 density factor and a 30-cm carbon reflector zone are used.

The neutronic analyses were performed in cylindrical geometry using the one-dimensional discrete ordinates transport code ANISN.⁽⁶⁾ The nuclear data from DLC-37⁽⁷⁾ and MACKLIB⁽⁸⁾ library based on ENDF/B-IV are used. The transport

TABLE II. Fuel Cycle Parameters for LWR and HWR Reactors^a

Reactor Type:	LWR				HWR
Fuel Cycle:	U Cycle with Pu Makeup	Th Cycle with Pu Makeup	Denatured U Cycle with ²³³ U Makeup	Denatured Th Cycle with ²³³ U Makeup	Denatured Th Cycle with ²³³ U Makeup
Fuel burnup, MWD/kg	30.4	33.4	33	35.3	16
Fissile enrichment	3.25	4.76	2.4	3.0	1.46
Initial core loading, kg/GWe					
²³⁹ Pu + ²⁴¹ Pu	923.3	1140	0	0	0
²³³ U	0	0	1210	1582	1648
²³⁵ U	177.9	0	159	33	0
Total	1101.2	1140	1369	1615	1648
Fissile consumption, kg/GWe-yr	442	508	463	287	102
Fissile Pu-generated, kg/GWe-yr	---	---	154	57	32

^aAt 0.75 capacity factor.

TABLE III. Hybrid Blanket Configurations

Blanket No.	Zone Thickness (cm)	Zone Composition by Volume	Comments
A	225	Vacuum	Plasma
	25	Vacuum	Scrape-off
	1	50% Inconel-718 + 50% He	First wall
	V^a	70% U_3Si + 10% Inconel-718 + 20% He	^{239}Pu breeder
	50	70% Li_2O + 10% Inconel-718 + 20% He	T-breeder
	30	90% C + 5% Inconel-718 + 5% He	Reflector
B	225	Vacuum	Plasma
	25	Vacuum	Scrape-off
	1	50% Inconel-718 + 50% He	First wall
	V^a	70% ThO_2 + 10% Inconel-718 + 20% He	^{233}U breeder
	50	70% Li_2O + 10% Inconel-718 + 20% He	T-breeder
	30	90% C + 5% Inconel-781 + 5% He	Reflector
C	225	Vacuum	Plasma
	25	Vacuum	Scrape-off
	1	50% Inconel-718 + 50% He	First wall
	50	70% U_3Si + 10% Inconel-718 + 20% He	^{239}Pu breeder
	30	90% C + 5% Inconel-718 + 5% He	Reflector
D	225	Vacuum	Plasma
	25	Vacuum	Scrape-off
	1	50% Inconel-718 + 50% He	First wall
	50	70% U_3Si + 10% Inconel-718 + 20% He	^{233}U breeder
	30	90% C + 5% Inconel-718 + 5% He	Reflector

^aVariable thicknesses from 5-25 cm.

calculations were done with 46 neutron and 21 gamma-ray group structures with S_4P_3 approximation.

HYBRID BLANKET PERFORMANCE

Neutronic calculations were carried out for the different blankets to determine their fissile production rate, tritium breeding ratio, and blanket energy multiplication. All the calculations were done at the beginning of life, i.e. with natural material without any concentrations of ^{233}U or ^{239}Pu in the blankets. Figure 1 shows the results of the calculations for blanket A with a DT fusion driver as a function of the fissile breeder zone thickness. The tritium-breeding ratio from these blankets decreases as the fissile breeder zone thickness increases. This design achieves a tritium-breeding ratio of one at 14-cm zone thickness for the fissile breeder.

The fissile production rate per fusion neutron and reactor blanket energy multiplication, MR (MR = total output energy per fusion event/total energy from the fusion event), increases as the fissile breeder zone thickness increases. Figure 2 shows similar behavior for the thorium oxide blanket with a DT fusion reactor. Figure 3 and Table IV represents the results for the different blankets with a DD fusion reactor. The fissile material generation rates in kg/MWth-yr of the reactor power are given in Table IV, where the thorium oxide blankets show a better performance with respect to the fissile production rate per MWth of the reactor power. This result has a large impact on the number of fission reactors which can be fueled per fusion breeder.

The DD fusion breeders show a higher fissile generation rate because the tritium breeding requirement is removed from the blanket which releases more neutrons for fissile production. As mentioned earlier, the blanket analyses were performed at the beginning of life. The blanket exposure will affect the basic performance of the system.⁽⁹⁻¹¹⁾ As the fissile material concentration

Fig. 1. Uranium silicide blanket performance with tritium capability versus plutonium breeder zone thickness for DT fusion breeder.

Fig. 2. Thorium oxide blanket performance with tritium capability versus ^{233}U breeder zone thickness for DT fusion breeder.

Fig. 3. Fissile production from U_3Si or ThO_2 breeder blanket versus breeder zone thickness for DD fusion driver.

TABLE IV. Energy Multiplication Factor and Fissile Production Rates for Different Fusion Drivers^a

Blanket	Fusion Breeder	Breeder Material	Breeder Zone Thickness (cm)	Energy Multiplication	Fissile Material (kg/MWth-yr)
A	DT	U ₃ Si	5	4.13	0.42
	DT	U ₃ Si	10	5.84	0.57
	DT	U ₃ Si	15	6.89	0.69
	DT	U ₃ Si	20	7.95	0.77
	DT	U ₃ Si	25	7.98	0.84
B	DT	ThO ₂	5	1.49	0.59
	DT	ThO ₂	10	1.62	1.02
	DT	ThO ₂	15	1.69	1.37
	DT	ThO ₂	20	1.72	1.69
	DT	ThO ₂	25	1.73	1.96
C	DD	U ₃ Si	50	5.64	0.95
D	DD	ThO ₂	50	1.42	2.3

^aAt 0.75 availability factor.

builds up, the burnup rate increases. This leads to more thermal energy per fusion neutron, higher tritium breeding ratio, and decreases the net fissile production rate. The changes in the blanket parameters are related to the discharge scenerio of the breeder zone. It is not desirable to have such changes during the reactor operation. It may be possible that these changes can be controlled within acceptable bounds. For example, if the blanket fertile material is not changed in order to build up a fissile material concentration of 4% the thermal power will double at the end of life. This increase in thermal power can be reduced to less than 15% peak to average by using a fuel management scenario based on four batches. In this scheme one quarter of the blanket is replaced every 1% increase in the fissile material concentration. In addition a fuel shuffling scenario every batch replacement can achieve a further reduction in the power peaking.

HYBRID ENERGY SYSTEM

Table V summarizes the results for different systems based on the information discussed in the previous sections. One can see from Table V that the fuel cycles based on thorium support a larger number of fission reactors per hybrid breeder than the other fuel cycles. The DD fusion driver exhibits a higher support ratio than the DT fusion breeder for the same fuel cycle. In order to evaluate the potential of these systems, a simple economic analysis was performed to calculate the cost of electricity.

The cost of electricity for the entire system was calculated as follows:

$$\text{Electricity cost} = \frac{\text{total annual cost}}{\text{total annual electrical output}} .$$

In order to calculate the total annual cost, the capital cost of the fusion breeders and fission burners are calculated as shown in Tables VI-a and VI-b.

TABLE V. Support Ratio for Different Fission Burners

Reactor Type:	LWR				HWR
Fuel Cycle:	U Cycle with Pu Makeup	Th Cycle with Pu Makeup	Denatured U Cycle with ^{233}U Makeup	Denatured Th Cycle with ^{233}U Makeup	Denatured Th Cycle with ^{233}U Makeup
DT fusion breeder					
with U_3Si blanket	5.0	4.4	---	---	---
with ThO_2 blanket	---	---	$6.4 + 2.2^a$	$10.3 + 1.3$	$29.1 + 2.1$
DD fusion breeder					
with U_3Si blanket	7.2	6.2	---	---	---
with ThO_2 blanket	---	---	$16.6 + 5.7$	$26.7 + 3.4$	$75.2 + 5.4$

^aIt means 6.4 LWR denatured U fuel cycle with ^{233}U makeup plus 2.2 LWR U fuel cycle with Pu makeup.

TABLE VI-a. Cost Estimate of Fission Burner Side of the Energy System

Fission Burners:	LWR			HWR	
	U Cycle with Pu Makeup	Th Cycle with Pu Makeup	Denatured U Cycle with ²³³ U Makeup	Denatured Th Cycle with ²³³ U Makeup	Denatured Th Cycle with ²³³ U Makeup
Fission burner capital cost, \$/kWth ^a	284	284	284	284	380
Annual cost on the fission burner capital at 16%, \$/kWth-yr	45.4	45.4	45.4	45.4	60.8
Fuel cycle cost, ^b \$/kWth-yr	7.4	6.8	6.7	6.4	11.8
Operating cost, ^c \$/kWth-yr	10	10	10	10	11.5

^aThe LWR costs \$284/kWt, the HWR costs 1.15, the cost of LWR plus \$160/kWe for heavy water. (13)

^bFuel cycle costs are \$620 and \$515/kg for LWR and HWR respectively; it covers the fabrication, spent fuel shipping, and reprocessing cost.

^cReference 1.

TABLE VI-b. Cost Estimate of Fusion Driver Side of the Energy System

Fusion Driver	DT	DD
Hybrid capital cost, \$/kWth	$284 F_{DT}$	$284 F_{DD}$
Annual cost on the fusion driver capital at 16%, \$/kWth-yr	$45.4 F_{DT}$	$45.4 F_{DD}$
Fuel cycle cost, ^a \$/kWth-yr	12.1	12.1
Operating cost, ^b \$/kWth-yr	10	10

^aFuel cycle costs are \$200/kg, 6 MWD/kg for U and \$330/kg, 10 MWD/kg for Th.

^bReference 12.

The capital cost for the fission burners are estimated with data from Refs. 1 and 13. The cost of the fusion breeder is uncertain. A survey of the existing fusion reactor studies without fission blanket shows a wide range for capital cost in terms of \$kWth. The capital cost for the DT breeder is estimated for the purpose of this study to be 2.5 times the LWR cost of equivalent thermal power. The LWR used in this study costs 284 kWth and produces electricity at 35.2 mills/kWh with a 16% rate of return on capital.⁽¹³⁾ The DD fusion breeder is assumed to cost twice the DT fusion breeder, which may be quite conservative. The cost of electricity for the different energy systems given in Table V are presented in Table VI-c. The denatured fuel cycles with ^{233}U fissile materials show the lowest cost for generating electricity. The large capital cost of the DD fusion driver does not impact the cost of electricity. One can see that the cost of electricity from both fusion breeders is the same for the denatured fuel cycles with ^{233}U fissile material. The DD fusion breeder has the advantage of supporting more fission burners, 2.6 times the DT fusion breeder.

CONCLUSIONS

This study has been carried out in order to investigate the characteristics of an energy system to produce a new source of fissile fuel for existing fission reactors. The denatured fuel cycles were used because of possible additional proliferation resistance compared to other fuel cycles. DT and DD fusion drivers were examined in this study with a thorium or uranium blanket for each fusion breeder. Various fuel cycles were examined for light-water reactors (LWR); uranium fuel cycle with ^{239}Pu makeup, thorium fuel cycle with ^{233}Pu makeup, denatured uranium fuel cycle with ^{233}U makeup, and denatured thorium fuel cycle with ^{233}U makeup. In addition, the last fuel cycle was used for heavy-water reactors (HWR) to utilize the excellent performance of the moderator in these reactors. The cost of electricity for the different energy systems was

TABLE VI-c. Electricity Cost from the Various Energy Systems

Fission Reactor Type:	LWR				HWR
Fuel Cycle:	U Cycle with Pu Makeup	Th Cycle with Pu Makeup	Denatured U Cycle with ^{233}U Makeup	Denatured Th Cycle with ^{233}U Makeup	Denatured Th Cycle with ^{233}U Makeup
DT fusion breeder ^a					
System capacity, GWe	6	5.4	9.6	12.6	32.2
No. of fission burners	5	4.4	8.6	11.6	31.2
Electricity cost, mills/kWh	34.2	34.6	31.9	30.9	38.6
DD fusion breeder ^b					
System capacity, GWe	8.2	7.2	23.3	31.1	81.6
No. of fission burners	7.2	6.2	22.3	30.1	80.6
Electricity cost, mills/kWh	39.1	40.3	32.2	31.0	38.7

$${}^a_{\text{F}_{\text{DT}}} = 2.5.$$

$${}^b_{\text{F}_{\text{DT}}} = 5.0.$$

calculated. The capital cost of the fusion breeder was normalized to the cost of a LWR reactor. The energy system is viewed as a one-hybrid reactor supplying the fissile fuel for a large number of fission burner reactors.

This study on fusion-fission hybrid energy systems leads to the following conclusions:

- (1) An energy system based on the denatured thorium fuel cycle achieves the lowest electricity cost compared to the different systems considered in this study.
- (2) The cost of electricity in mills/kWe from the denatured thorium energy system is lower than the cost from the existing fission reactors due to the saving in the fuel cost.
- (3) A self-sufficient energy system of 31.1 GWe is achieved with 1 GWe DD fusion driver. The equivalent DT fusion driver supports an energy system of 12.6 GWe.
- (4) The cost of electricity from the DD or DT fusion driver is about the same except the DD fusion driver supports more fission reactors. It is shown that the DD hybrid energy system supports 2.5 times more burner reactors.
- (5) The fission burners with denatured thorium fuel cycle generate more than 82% of the total energy of the system which improve the system proliferation resistance.

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