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The Fusion-Fission Hybrid As an Alternative

to the Fast Breeder Reactor

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CONTENTS

THE FUSION-FISSION HYBRID AS AN ALTERNATIVE TO THE FAST BREEDER REACTOR

by

R. J. Barrett and R. W. Hardie

ABSTRACT

This report compares the fusion-fission hybrid on the plutonium cycle with the classical fast breeder reactor (FBR) cycle as a long-term nuclear energy source. For the purpose of comparison, the current light-water reactor once-through (LWR-OT) cycle was also analyzed. The methods and models used in this study were developed for use in a comparative analysis of conventional nuclear fuel cycles. Assessment areas considered in this study include economics, energy balance, proliferation resistance, technological status, public safety, and commercial viability. In every case the characteristics of all fuel cycle facilities were accounted for, rather than just those of the reactor.

I. INTRODUCTION

One of the principal goals of energy research is the development of a technology that provides a long-term, nearly inexhaustible source of electric power. Two of the prime candidates, fission and fusion, rely on the energy released by nuclear reactions.

Nuclear fission has been a viable source of electrical energy for two decades, but major changes in the reactors and in their fuel cycles will be required if fission is to be a long-term source of energy. To this end, several countries have pursued the development of a fast breeder reactor (FBR) and the introduction of spent fuel reprocessing. As a result of an aggressive worldwide development program, the plutonium-fueled FBR will soon be commercially available.

1

The most favorable nuclear fusion reaction involves combining deuterium and tritium to produce helium and an energetic neutron:

$$D + T \rightarrow {}^4He + n(14.1 \text{ Mev}).$$
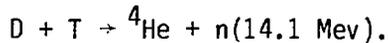
This reaction can only take place under carefully controlled conditions, and producing those conditions requires the consumption of large quantities of electrical energy. After decades of work on the fusion process, researchers have yet to operate a fusion reactor which can generate as much energy as it consumes. Furthermore, fusion will not be a commercial reality until the energy output is several times higher than the energy input. Attaining that type of performance will require many more years of development work.

The fusion-fission hybrid has been proposed as a short cut to fusion commercialization. In this concept, the energetic neutrons from the fission reaction are captured in a blanket of fertile material, thereby breeding fissile fuel, which can be reprocessed for use in conventional fission reactors. The hybrid also produces a great deal of electricity, some or all of which is consumed within the plant itself.

Although the fusion-fission hybrid is an outgrowth of fusion research, it is essentially a fission energy system. Almost all of the energy produced is due to fission reactions, either in the hybrid blanket or in the fission reactors it supports. Furthermore, the hybrid requires the same type of fuel cycle facilities as does the fast breeder reactor. Thus, the hybrid should be viewed as a direct competitor to the FBR as a long-term source of fission energy.

This study compares the fusion-fission hybrid and the classical FBR as producers of plutonium for consumption in light water reactors (LWRs). As a benchmark for comparison, the current light-water reactor once-through (LWR-OT) cycle has also been analyzed.

Several assessment areas were considered in the comparisons. These include economics, proliferation vulnerability, net energy potential, technological readiness, public safety, and a number of institutional questions. In all phases of the evaluation, we have tried to assess the impact of the entire fuel cycle, rather than concentrating on any one facility. Our basic methodology, developed as part of an alternative nuclear fuel cycle study, is described in greater detail in Ref. 1.

2

II. CONCLUSIONS

The fusion-fission hybrid on the plutonium cycle can be a long-term source of nuclear energy. The hybrid cycle can derive about one-hundred times as much net energy from the uranium resource as can the current LWR-OT cycle. Although this is somewhat lower than the net energy potential of the classical FBR cycle, there is no reason to discriminate on this basis. Judged on any realistic time scale, both the classical FBR and the hybrid cycles are nearly inexhaustible sources of energy.

The levelized cost of power from the hybrid cycle depends greatly on the performance of the fusion driver. However, for a reasonable choice of performance parameters, the cost of power from the hybrid cycle does not differ significantly from the classical FBR and LWR-OT cycles. There appears to be no economic incentive for preferring one or the other long-term fuel cycle.

We perceive no significant difference in the proliferation potential of the classical FBR and hybrid cycles.

Given the lack of experience with hybrid reactors, it is not possible to assess their health and safety implications in a realistic fashion. We conclude that the overall risk associated with the hybrid cycle is similar to that of the classical FBR cycle.

The crucial difference between these two cycles is one of readiness. Although the fast breeder reactor will almost certainly be a commercial technology in the near future, the fusion-fission hybrid has yet to be proven scientifically feasible. The investment of time and money required to commercialize the hybrid cycle could only be justified by a real or perceived advantage of the hybrid over the classical FBR. Our analysis leads us to conclude that no such advantage exists. Therefore, there is not sufficient incentive to demonstrate and commercialize the fusion-fission hybrid.

III. DESCRIPTION AND MODELING OF FUEL CYCLE SYSTEMS
A.   Fusion-Fission Hybrid Fuel Cycle

The principal components of a fusion-fission hybrid fuel cycle are the fusion reactor and the fission blanket. The fusion reactor produces thermonuclear power while the fission blanket produces fissile fuel by capturing neutrons in fertile fuel and also multiplies the thermonuclear power generated in the fusion reactor. Therefore, a fusion-fission hybrid can have two distinct products--electricity and fissile fuel.

3

Figure 1 is a schematic diagram of the energy flow in a fusion-fission hybrid. The symbols used in this diagram are defined as follows:

Q_n = ratio of the fusion neutron energy to the injected energy;

E_n = neutron thermonuclear thermal energy;

M_n = blanket multiplication of the fusion neutron energy;

F = fissile fuel production rate;

T = *tritium production rate;*

E_a = alpha particle thermal energy;

E_I = plasma driver thermal energy;

n_t = turbine thermal efficiency;

E_e = gross electrical energy;

E_{net} = net electrical energy;

E_c = recirculating electrical energy, and

n_d = plasma driver efficiency.

POWER FLOW DIAGRAM
## OF A FUSION-FISSION HYBRID
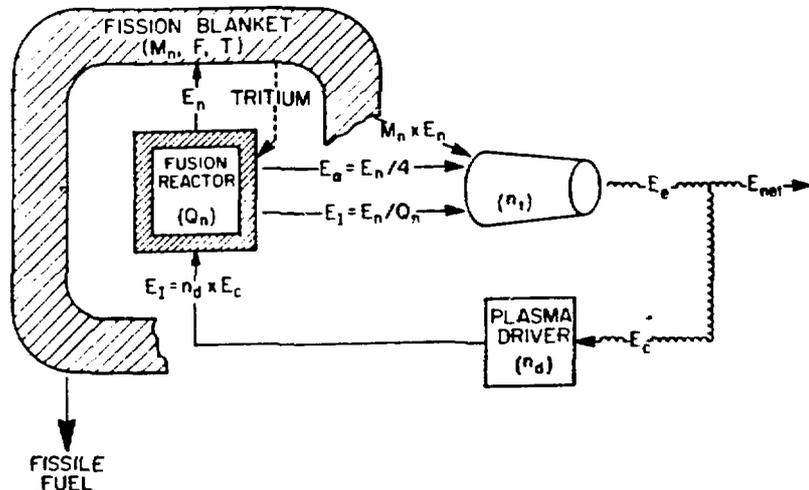
Fig. 1. Energy flow diagram of a fusion-fission hybrid.

An important problem facing fusion-fission hybrid designers is the tradeoff between fissile fuel production and electrical energy production. That is, the electrical energy is increased by increasing M_n, the blanket multiplication of the fusion neutron energy. However, increasing M_n decreases F, the fissile fuel production rate. The relationship between fissile fuel production and energy multiplication can be approximated by the following two equations.[2]

$$F = (1 - T) + (\varepsilon - p) + c(\hat{\nu} - 1) + s[\nu - 2(1 + \alpha)], \text{ and}$$

$$M_n = \frac{1}{14.1} \quad 14.1 + E_f(c + s) \quad ,$$

where

      F = net number of fissile atoms produced per neutron entering the blanket;

      T = number of neutrons absorbed in Li^6 per fusion neutron;

      ε = neutron multiplication through (n,2n) and (n,3n) reactions in the blanket per neutron entering the blanket;

      P = parasitic absorptions and leakage per neutron entering the blanket;

      c = number of fissions in fertile nuclei per neutron entering the blanket;

      $\hat{\nu}$ = average number of neutrons produced per fission of fertile nuclei;

      s = number of fissions in fissile nuclei per neutron entering the blanket;

      ν = average number of neutrons produced per fission of fissile nuclei;

      α = capture-to-fission ratio in the fissile nuclei; and

    E_f = energy release per fission (MeV).

The above equations for fissile fuel production and blanket multiplication are expressed in terms of neutrons entering the blanket. These parameters can also be expressed in terms of neutrons produced by the fusion process:

$$F' = \Delta\Omega \left[F + \left(\frac{\Delta\Omega - 1}{\Delta\Omega} \right) T \right]$$

$$M_n' = \Delta\Omega \times M_n$$

where $\Delta\Omega$ is the fraction of fusion neutrons entering the blanket. The primes indicate that the parameters are per fusion neutron.

Because there is a tradeoff between fissile fuel production and electrical energy production, three combinations of F and M_n were evaluated. These were

$M_n = 10$, F = 2.05;

$M_n = 20$, F = 1.67; and

$M_n = 30$, F = 1.29.

In addition, for each of the above combinations, three different values for Q_n were considered--0.5, 1.0, and 5.0. Table I presents the parameters assumed for this analysis. It should be emphasized that these parameters do not reflect any single fusion-fission hybrid reactor design, but are a composite of several designs. The assumptions used to calculate these parameters are also shown.

The primary components in a fusion-fission hybrid fuel cycle system are the hybrid reactor and satellite reactors. As described above, the hybrid reactor produces both fissile fuel and electricity while the satellite reactors consume fissile fuel and produce electricity. Other components in the system include fabrication, reprocessing, and waste storage facilities. The interaction of the various components is shown in Fig. 2.

Although a fusion-fission hybrid could be used to produce either uranium-233 or fissile plutonium, this analysis was limited to fissile plutonium production. Therefore, the satellite reactor chosen for this analysis (LWR-Pu+U) is a plutonium-fueled light-water reactor with uranium-238 as fertile fuel. The reactor was based on a 1270-MWe (3800-MWt) Combustion Engineering, Inc. pressurized-water design. Detailed data for this reactor are presented in Ref. 1. A summary of these data is presented in Tables II and III where the fuel management data are averaged over the lifetime of the reactor to simulate equilibrium.

TABLE I

FUSION-FISSION HYBRID PARAMETERS

Performance Parameters	Ratio of Neutron Thermonuclear Power to Injected Power Q_n	Fusion Thermal Energy (MWt)	Fission Thermal Energy (MWt)	Fusion Neutron Thermal Energy (MWt)	Net Electrical Production (MWe)	Fissile Fuel Production (kg/yr)	Initial HM[a] Loading (kg HM)	HM Throughput (kg HM/yr)[a]	Fuel Burn-up (MWt-d/kg HM)[a]
	0.5	1000	2000	308	53	1542	523 600	154 200	3.3
$M_n = 10$									
$F = 2.05$	1.0	771	2229	343	473	1719	583 100	171 900	3.3
$F' = 1.29$									
$s = 0.035$	5.0	547	2453	377	884	1892	640 900	189 200	3.3
	0.5	565	2435	174	465	679	295 800	67 900	9.2
$M_n = 20$									
$F = 1.67$	1.0	415	2585	184	716	721	312 800	72 100	9.2
$F' = 1.01$									
$s = 0.740$	5.0	282	2718	194	940	758	329 800	75 800	9.2
	0.5	394	2606	121	627	339	205 700	33 900	19.7
$M_n = 30$									
$F = 1.29$	1.0	284	2716	126	806	353	214 200	35 300	19.7
$F' = 0.72$									
$s = 1.445$	5.0	190	2810	131	960	365	222 700	36 500	19.7

Assumptions: Total thermal energy = 3000 MWt
Capacity factor = 70%
$T = 1.0$
$\varepsilon - p = 0.33$
$c = 0.60$
$\Delta\hat{\Omega} = 0.75$
$\hat{v} = 3.9$
$v = 2.9$
$E_f = 200$
$\alpha = 0.72$
$\eta_t = 0.33$
$\eta_d = 0.65$
HM Loading = 1.7×10^3 kg HM/fusion neutron thermal energy
HM throughput assumes 1% produced fissile material in discharged fuel

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[a]HM is "heavy metals."
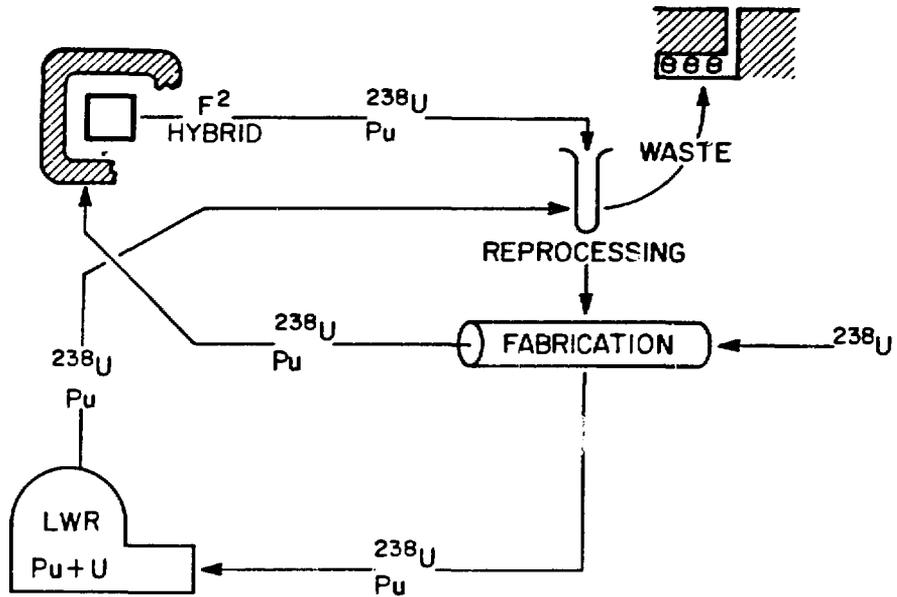
Fig. 2.   Fusion-fission hybrid fuel cycle.

TABLE II

REACTOR CHARACTERISTICS[a]

| | | Lifetime Requirements | | Equilibrium Conditions | |
Reactor	Power Level (MWe)	U_3O_8 (tons U_3O_8/GWe) [Charge Discharge Net (c-d)]	Enrichment (10 kg SWU/GWe)[b] [Charge Discharge Net (c-d)]	Fabrication Requirements [MTHM/(GWe·yr)][c]	Core Discharge Exposure (MWd/kg HM)[d]
FBR-Pu+U/U/U	1196	0 0 0	0 0 0	13.0/7.3/5.9[e]	62
LWR-Pu+U	1270	987 0 987	0 0 0	27.0	30

[a]Values do not include losses such as fabrication and reprocessing losses. Capacity factor is 70%.

[b]SWU is "separative work units."

[c]MTHM is "metric tons of heavy metals."

[d]MWd is "megawatt/days."

[e]Core/Axial Blanket/Radial Blanket.

8

TABLE III

AVERAGE FISSILE MASS FLOWS[a]
[kg/(GWe·yr)]

Reactor	233U [Charge Discharge Net (c-d)]	235U [Charge Discharge Net (c-d)]	Fissile Pu [Charge Discharge Net (c-d)]	Total Fissile [Charge Discharge Net (c-d)]
FBR-Pu+U/U/U	0 0 0	73 51 22	1312 1634 -322	1385 1685 -300
LWR-PU+U	0 0 0	180 112 68	1080 851 229	1260 963 297

[a]Values do not include losses such as fabrication and reprocessing losses. Capacity factor is 70%.

B.   Classical Fast Breeder Reactor Cycle

Conceptually, the classical fast breeder reactor fuel cycle (Fig. 3) is similar to the fusion-fission hybrid cycle. The principal difference is that
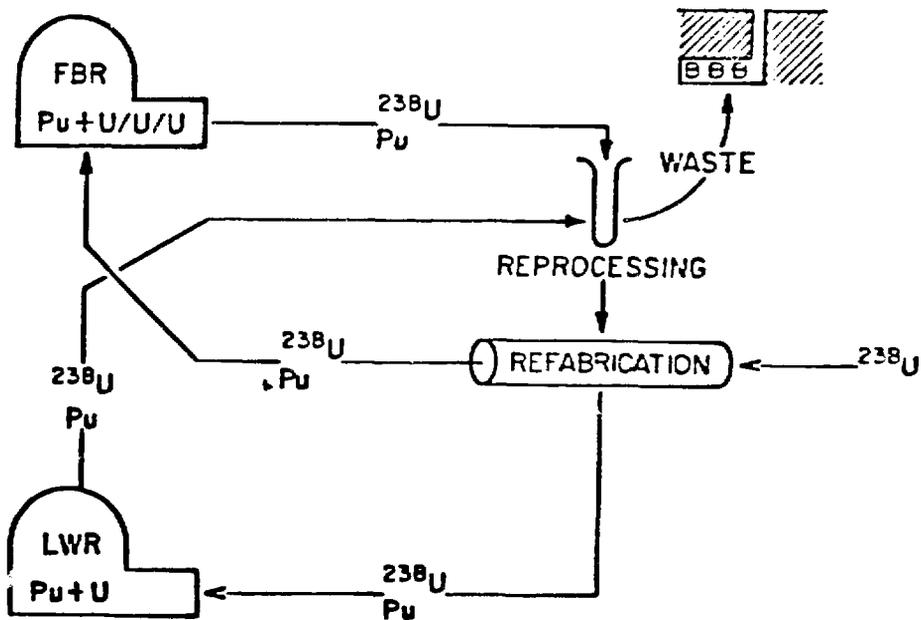

Fig. 3.   Classical FBR plutonium fuel cycle system.

9

the fusion-fission hybrid is replaced by an FBR as the source of fuel for the plutonium-fueled LWR.

The FBR used in this analysis is based on a typical 1200-MWe (3736-MWt) advanced oxide design. The breeding ratio for this design is 1.355, the conversion ratio is 1.040, and the average core discharge exposure is 62 MWd/kg. Detailed data for this reactor are presented in Ref. 1, and summary data are presented in Tables II and III.

The plutonium-fueled LWR is identical to the design used for the fusion-fission hybrid cycle described above.

C.   Systems Integration Model

A key feature of this analysis is that the evaluation encompasses total, integrated fuel cycle systems. A description of the Systems Integration Model (SIM) computer code used in the analysis is contained in Ref. 1. Basically, SIM characterizes the relationships of the various fuel cycle components into an integrated system. For the fusion-fission hybrid system, one of the most important results from SIM is the fractional electrical contribution of the hybrid and the satellite reactor. That is, the fraction of the system power produced by the hybrid varies considerably depending on whether the hybrid is primarily a fissile fuel producer or primarily an electricity producer.

Hybrid power fractions for the hybrid design parameters discussed earlier in this section are presented in Fig. 4. The fraction of power produced by the hybrid varies from almost zero to about 0.38.

SIM results for the classical FBR fuel cycle, normalized to a 1GWe system operating at 70% capacity factor, are shown in Fig. 5. For this fuel cycle, the fraction of power produced by the FBR is 0.46.

IV. ENERGY ANALYSIS

The most fundamental measure of a system that supplies electricity is the total amount of energy it can deliver to the distribution grid. There is little incentive to develop a technology that exploits a limited energy resource, utilizes a small fraction of a resource, or consumes nearly as much energy as it produces.

The nuclear fuel cycles considered in this study are designed to exploit our reserves of uranium. Although there is uncertainty about the size of that resource, it is definitely larger than the combined world reserves of gas, oil and coal.[3]

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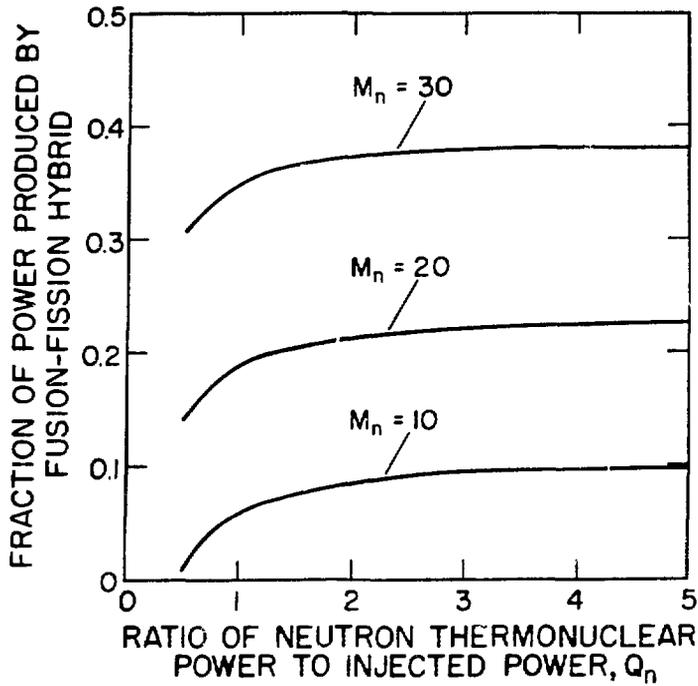
Fig. 4. Fraction of power produced by fusion-fission hybrid.
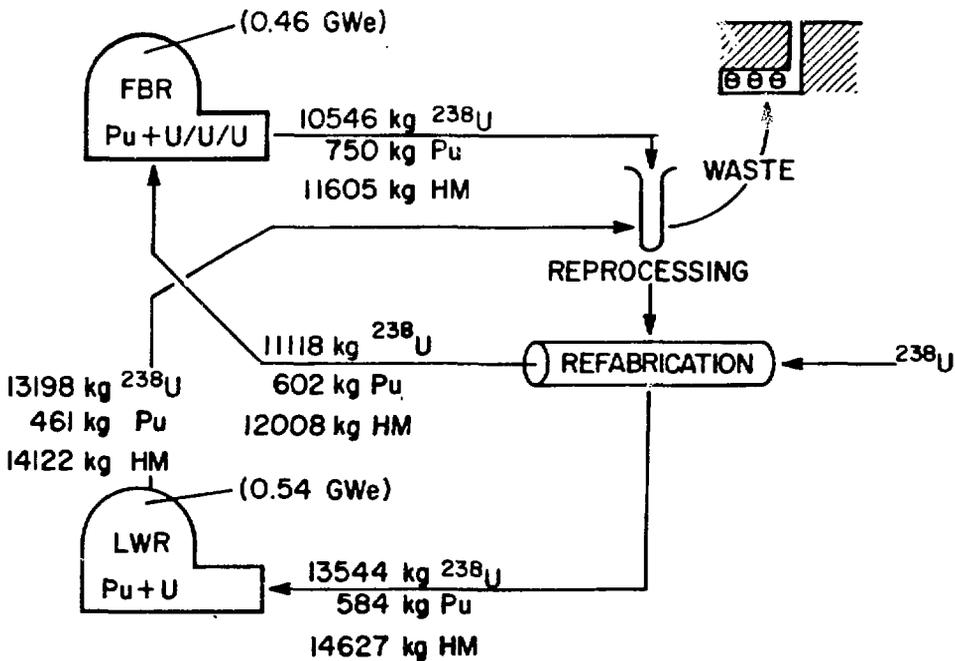
Fig. 5. Classical FBR plutonium fuel system.

The ability of a particular nuclear fuel cycle to extract energy from uranium is called its uranium utilization fraction F_u, a parameter calculated from fuel management data. Because all nuclear fuel cycles discard or lose some uranium, F_u is always less than unity. The LWR-OT cycle extracts only 0.5% of the energy value of natural uranium ($F_u = 0.005$). Most of the energy remains unused in the form of enrichment tails and spent fuel. The classical FBR cycle is designed to use all of the uranium, but losses experienced during repeated reprocessing and refabrication limit its uranium utilization fraction to 0.63.

Uranium utilization in the hybrid cycle is somewhat lower than in the classical FBR cycle. Furthermore, F_u will vary as a function of the blanket parameters, F and M_n. This is due principally to the fact that a higher value of M_n, the energy multiplication, will result in a lower reprocessing requirement for the same energy output. The resulting decrease in reprocessing losses will slightly enhance resource utilization.

Fuel-cycle efficiency $_c$ is defined as the fraction of energy produced that actually reaches the distribution grid. It is always less than unity because some energy is required to operate the reactors and fuel-cycle facilities. Some energy is also consumed in the construction of fuel-cycle facilities.

The LWR-OT cycle has a fuel-cycle efficiency of 0.93; most of the losses are due to the recirculating of energy in the power plant and the high electricity demand of uranium enrichment plants. Efficiency of the classical FBR system is about 0.97. The small fraction of energy lost is due mainly to recirculation of energy in the power plants.

Energy efficiency of the hybrid cycles depends mostly on the performance of the fusion driver. As the plasma multiplication Q_n decreases, an increasing fraction of the hybrid's energy output must be recirculated to drive the fusion reaction. For the range of performance parameters considered in this study, fuel cycle efficiency will range from 0.85 to 0.96.

Our overall figure of merit is the net energy potential η. This parameter is defined as the product of the uranium utilization fraction and the fuel cycle efficiency:

$$\eta = \varepsilon_c \times F_u \quad .$$

This parameter represents that fraction of the uranium energy which can ultimately be delivered to the electrical distribution system. Because it is expressed as a fraction of the uranium resource, it will not change as resource estimates are revised and updated.

Results of the energy analysis are presented in Table IV and in Fig. 6. The LWR-OT cycle has a very low net energy potential. For this reason, it is generally regarded as a short-term nuclear option. Both the classical FBR and hybrid* cycles represent an improvement of about a hundredfold over the LWR-OT cycle. Although the classical FBR cycle has an appreciable advantage over the hybrid, there is no reason to discriminate on this basis. Judged on any realistic time scale, these two fuel cycles are both long-term, nearly inexhaustible sources of nuclear energy.

V.   ECONOMICS

A.   Introduction

A key criterion for evaluating any new method of generating electricity is economics. That is, the electrical bus bar cost must be competitive with other methods of generating electricity; otherwise the new technology will never be commercialized. Because of uncertainties in the cost data, it is impossible to precisely predict electrical generating costs of the fusion-fission hybrid system. Instead, the goal is to determine whether or not power costs for fusion-fission hybrid systems are roughly comparable to other methods of generating electricity. If not, hybrids should probably be dropped. If so, hybrids should be investigated further.

TABLE IV

ENERGY ANALYSIS RESULTS

LWR-OT	Classical FBR	Hybrid
0.0052	0.63	0.50 to 0.59
0.93	0.97	0.85 to 0.96
0.0048	0.61	0.43 to 0.57

*The net energy potential of the hybrid includes a small (0.1 to 2%) contribution from fusion reactions.
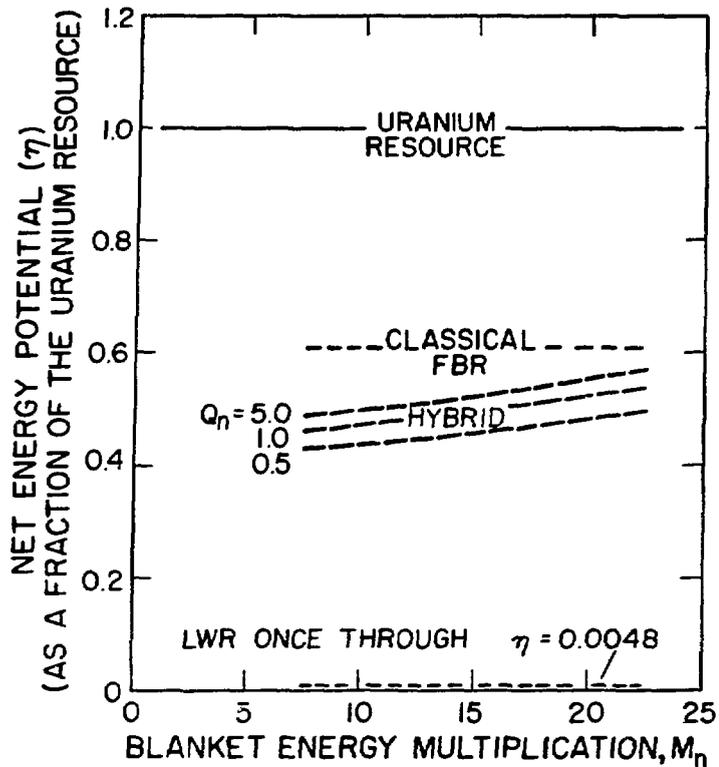
Fig. 6. Net energy potential of nuclear fuel cycles.

Another key goal in performing economics calculations for hybrid systems is to provide guidance to hybrid designers. From a power-cost viewpoint, these calculations can help determine whether hybrid reactors should be designed for high el production or high electrical energy production.

B. Methodology

The economics methodology used to calculate total power costs is described in Ref. 1. Basically, the model consists of a computer code, LPC, (Levelized Power Cost)[4] which calculates levelized total power costs on the fundamental assumption that incomes must balance expenses over the lifetime of a project. The expenses, such as return on investment, return of investment, and fuel costs, are assumed to be known. The incomes are revenues from the sale of electricity, where the price of electricity is calculated so that incomes equal expenses.

Economics analyses of fusion-fission hybrids are complicated somewhat because hybrids have two products--fissile fuel and electricity. Many

14

analyses assume a value for the bred fissile fuel and compare this value with the cost of producing the fuel in a hybrid. However, such a technique also requires an assumption of what the electricity is worth.

This analysis avoids the above problems by calculating the power cost of the complete system consisting of the hybrid reactor and the satellite reactor. The value of the fissile fuel is determined by the model using indifference price concepts, but this value is not really important because the fissile fuel is internal to the system. That is, fissile fuel sold by the hybrid is purchased by the satellite reactor, so the net cost to the system is zero. Reference 1 contains further description of indifference prices.

C. Economics Data Base

Except for fusion-fission hybrid reactor costs, all the economics data used in this analysis are presented in Ref. 1. Economics data for the fusion-fission hybrid reactor are given in Table V.

The most important cost parameter associated with the hybrid reactor is the capital cost. This analysis used the technique described by Bethe[5] to estimate the capital cost. Because the capital cost is dominated by the cost of the heat-removal system, that cost is assumed proportional to the thermal power.

The cost per MWt is postulated to be the same as for a fast breeder reactor, because their heat removal systems are of similar complexity. Another term is added to the capital cost to account for the complexity, and therefore the high cost, of the fusion driver.

TABLE V

KEY FUSION-FISSION HYBRID REACTOR COST PARAMETERS

Blanket Multiplication of the Neutron Energy, Mn	Ratio of Neutron Thermonuclear Power to Injected Power, Qn	Electrical Power Level (kMe)	Capital Cost ($/kMe)	Operation and Maintenance		Total Front End Fuel Cost ($/kg HM)[a]	Total Back End Fuel Cost ($/kg HM)[a]
				Fixed (10^6 $/yr)	Variable (10^6 $/yr)		
10	0.5	53	24 616				
10	1.0	473	2 592				
10	5.0	884	1 300				
20	0.5	465	2 484				
20	1.0	716	1 540	20.3	1.2	110	445
20	5.0	940	1 125				
30	0.5	627	1 747				
30	1.0	806	1 313				
30	5.0	960	1 068				

[a]HM is "heavy metals."

The resulting expression used to estimate the hybrid capital cost is

$$C_H = C_B + f \times C_F$$

where

C_H is the fusion-fission hybrid capital cost ($/kWt),

C_B is the classical FBR capital cost ($/kWt),

f is the fraction of thermal power produced by fusion, and

C_F is the added cost of fusion energy ($/kWt).

For this study, the FBR capital cost was taken to be $320/kWt, and the added cost of fusion energy was taken to be $345/kWt.

D.   Results

Levelized system total power costs as a function of the blanket multiplication, M_n, are shown in Fig. 7. Power costs were calculated for
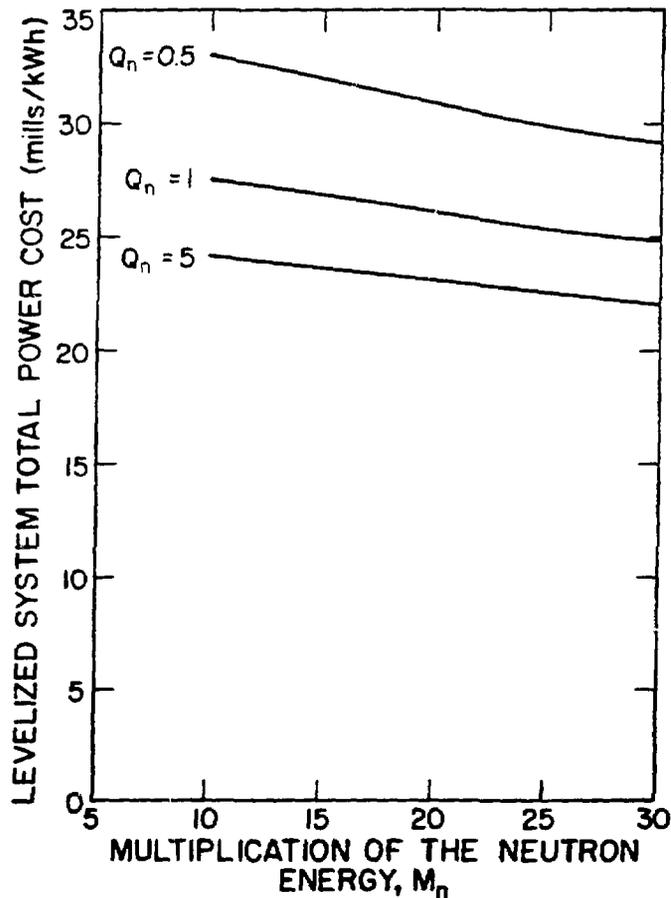
Fig. 7. System power cost for the fusion-fission hybrid.

16

three values of Q_n, the ratio of the neutron thermonuclear power to injected power. These data are cross-plotted in Fig. 8, where the results are shown as a function of Q_n.

For the assumptions used in this analysis there is a sharp decrease in total power cost as Q_n increases from 0.5 to 1.0. However, as Q_n increases from 1.0 to 5.0, the decrease in total power cost is much less sharp.

For all values of Q_n the total power cost decreases as M_n increases. This suggests that hybrid designers should emphasize electrical production rather than fissile fuel production. If the hybrid capital costs are arbitrarily increased by 50%, the results, shown in Fig. 9, point to the opposite conclusion.
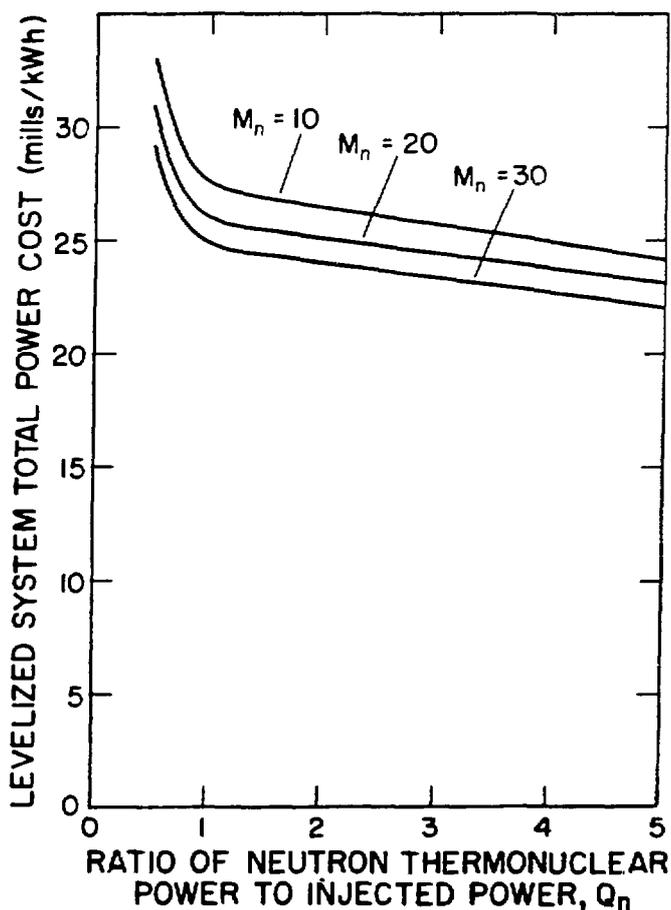
Fig. 8.   Sensitivity of system power cost to hybrid performance parameters.
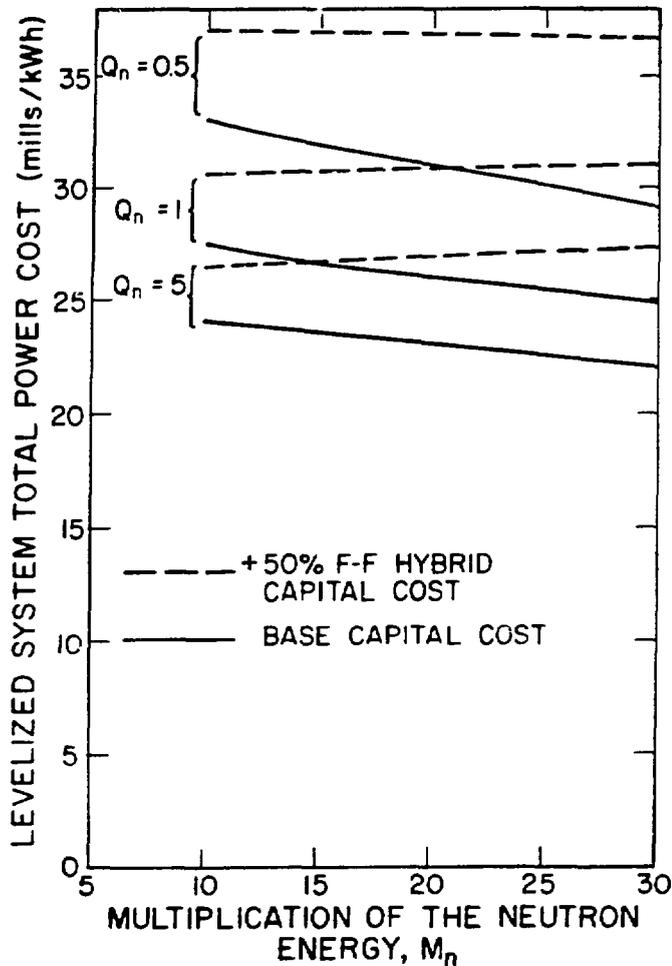
Fig. 9. Sensitivity of system power cost.

That is, for high hybrid capital costs, fissile fuel production should be emphasized over electrical production. This result is understandable because the satellite ratio is greater for higher fissile fuel production rates. As the satellite ratio increases, higher hybrid capital costs have less effect because the hybrid makes up a smaller percentage of the total system.

Finally, as a reference point, total power costs for a hybrid system were compared with the current nuclear fuel cycle. Power costs for a fusion-fission hybrid system with M_n = 10 and for a light-water reactor once-through (LWR-OT) cycle are presented in Fig. 10. For the hybrid system, the effect of varying Q_n from 0.5 to 5.0 is shown. For the LWR-OT cycle,

18

F^2 HYBRID SYSTEM
(M$_n$=10)

LEVELIZED POWER COSTS (mills/kWh)

Q$_n$=0.5

Q$_n$=1

Q$_n$=5

$160/lb U$_3O_8$

$100/lb U$_3O_8$

$40/lb U$_3O_8$

30

25

20

15

10

5

0

FUEL
+
O+M
+
CAPITAL

FUEL

O·M

CAPITAL

FUEL

O·M

CAPITAL

F^2 HYBRID
U

LWR
Pu+U

LWR
U5(LE)+U
(ONCE
THROUGH)
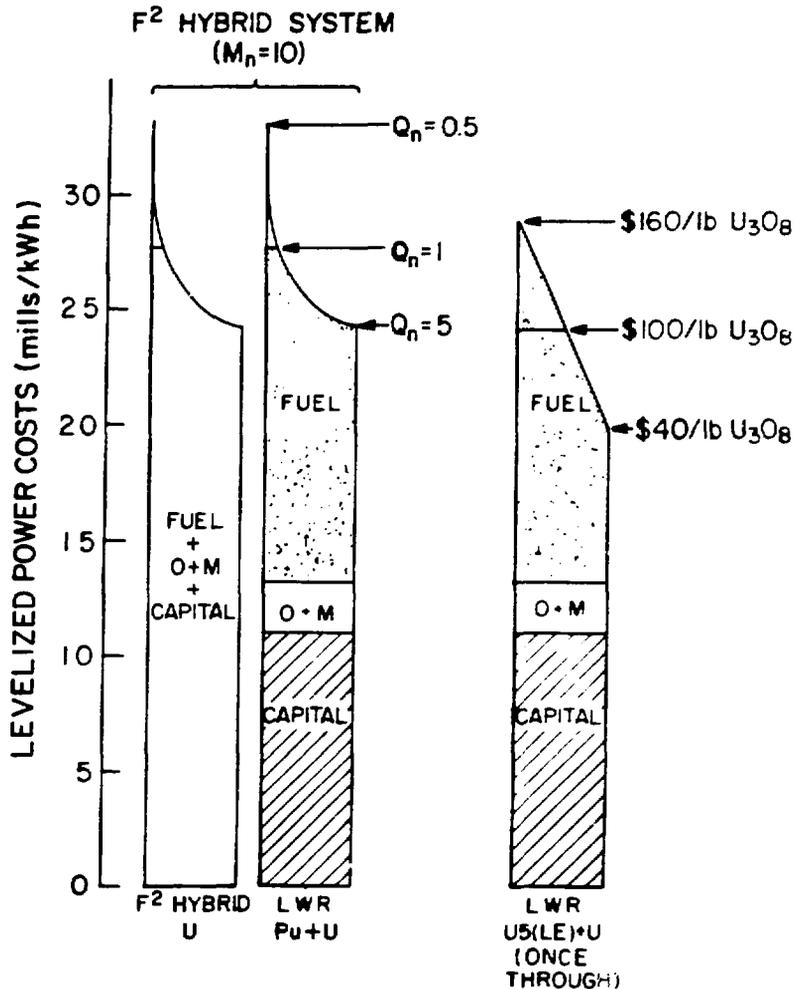
Fig. 10. Levelized power costs for the fusion-fission and LWR-OT systems.

the price of U$_3$O$_8$ was allowed to vary from $40/lb to $160/lb. Details of the calculations for the LWR-OT are given in Ref. 1.

The range of total power costs for the fusion-fission hybrid system is comparable to the LWR-OT cycle when the price of U$_3$O$_8$ rises above $100/lb. For comparison, the results for the classical fast breeder reactor fuel cycle are presented in Fig. 11. For the assumptions used in this analysis, the total power cost for the FBR system is comparable to the cost of the LWR-OT cycle when the price of U$_3$O$_8$ is around $100/lb. Therefore, the total power cost of the hybrid system for Q$_n$ in the range of 1 to 5 is comparable to that of FBR systems.

19
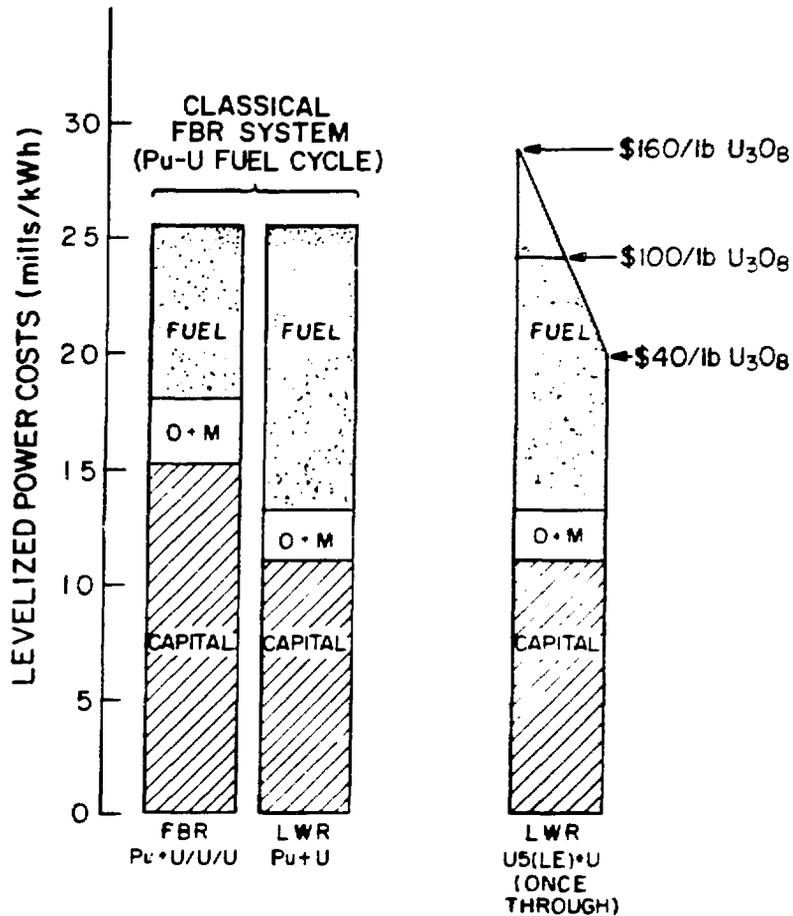
Fig. 11. Levelized power costs (mills/kWh).

There is one key difference in the economics of hybrid systems compared with FBR systems. Although hybrid reactors and fast breeder reactors both have large uncertainties, uncertainties in the hybrid parameters have less impact than uncertainties in the FBR parameters. The reason is that FBRs represent approximately half of the electrical capacity of the classical FBR system, whereas hybrid reactors account for a much smaller fraction of the capacity in the hybrid fuel cycle.

In summary, there is not much difference in total power cost among the various fuel cycle systems examined in Ref. 1 and in this report. Therefore, other considerations will play a strong role in the choice of the best long-term nuclear energy strategy for the United States.

VI. TECHNOLOGICAL EVALUATION

In assessments of the type presented in this report, we often must compare technologies which are at vastly different stages of development. Although we cannot reconcile such differences, we can identify and examine their severity. This type of question is addressed below in the section on "technological uncertainties."

The attractiveness of technologies can often change greatly as the values of key parameters vary from the reference case. In the section on "performance parameters," we examine variations in those properties which most affect the attractiveness of each fuel cycle.

A.   Technological Uncertainties

The state of readiness of competing technologies is an important point of comparison.

The major technological uncertainty associated with the LWR-OT cycle is the question of waste management. To adequately address the technical and political aspects of this problem is beyond the scope of this study. However, unless a satisfactory solution can be found, no nuclear fuel cycle will be able to operate.

The classical FBR system poses two additional requirements: 1) commercialization of the FBR and 2) modifications to the PUREX process to handle fuels with high plutonium concentrations. Given the current status of technology and the progress of ongoing development programs, there is little doubt that the classical FBR system could soon be ready for commercialization.

The fusion-fission hybrid system is the furthest from achieving commercial status. Development requirements for this cycle may be loosely grouped into three categories: (1) the achievement of sufficient plasma performance, (2) development of supporting technology, and (3) a program of hybrid demonstration and commercialization.

The figure of merit for plasma performance is Q_n. A viable fusion-fission hybrid should attain a value of Q_n approaching unity. For this criterion to be met, the plasma must reach and sustain "ignition," a state in which no outside source of energy is needed to heat the plasma. It is quite likely that experiments conducted as part of the pure fusion program will achieve this level of performance by 1990.

Most of the supporting technology required for hybrid reactors is being developed as part of the pure fusion program. Major items include superconducting magnets,* neutral beam heating, tritium-recovery systems and radiation-resistant materials. The fission blanket technology can be borrowed from the breeder program.

Thus, two of the three above-mentioned requirements for development of the hybrid can be attained without making any commitment to the hybrid itself. The required plasma performance and necessary supporting technologies will be available as a result of the pure fusion program and the breeder program.

It is the demonstration and commercialization phase which will require the major commitment of funds to the fusion-fission hybrid. This orderly process of scaling from small plant to large, improving reliability and efficiency, developing operating procedures, and working out problems is both costly and time-consuming. The decision to fund such a program will require a strong incentive of some type, especially if the decision comes at a time when the classical FBR cycle has already reached commercial status.

B.   Performance Parameters

A nuclear fuel cycle is not a static concept. There are tradeoffs and improvements which can be made to optimize the performance of each system. There is also the possibility that a system will not achieve the performance levels postulated in our description of it. In the discussion that follows we will examine potential performance parameter variations that could significantly alter the attractiveness of each cycle.

The continued health of the LWR-OT cycle is most strongly dependent on a continuing supply of uranium. Clearly, this cycle would benefit greatly from the discovery of new uranium deposits, but there are also improvements to the cycle itself which would enhance its uranium utilization.

For instance, the development of advanced enrichment technology, such as laser isotope separation, could reduce the fraction of fissile uranium discarded with the enrichment tails. Modifications to the LWR itself could improve uranium utilization by 15 to 30%. Any advancements in the mining and milling of low-grade uranium ore would also be a boom to the LWR-OT cycle. The cycle could be "closed" by reprocessing spent fuel and recycling unused

*An additional problem with superconducting magnets is uncertainty about the future supply of helium. However, there is a good possibility that the hybrid can operate with conventional magnets.

fissile material back to the LWRs. This strategy could reduce the uranium requirements by about 40%. However, closing the LWR-OT cycle would also fundamentally alter the economics and the proliferation potential of the system.

Although a combination of the improvements described above can extend the life of the LWR-OT cycle, it cannot alter the fact that this system is a short-term energy option.

The classical FBR cycle is much more sensitive to economics than to incremental changes in resource utilization. Total power cost will be most sensitive to the capital cost of the breeder reactors and the costs of reprocessing and refabrication services. These factors have been discussed in Sec. V.

Proliferation resistance is also an important issue which can be affected in several ways by technological developments. These factors will be discussed in Sec. VII.

Finally, the breeding ratio of the FBR can be an important parameter, because it affects the speed with which the breeder can produce plutonium. A breeding ratio that is only slightly greater than unity would be sufficient for steady-state operation, but when this cycle is beginning operation for the first time, a great deal of plutonium will be required to fuel the reactor cores. Breeding ratio will be the limiting factor in the rate of expansion of this cycle.

The principal performance parameters for the hybrid fall into three categories: fusion driver performance, fission blanket characteristics, and plant performance. The figure of merit for the fusion driver is really the product of n_d and Q_n. Calculations showed that a 50% reduction of this product from the reference value* (from 0.65 to 0.325) would increase levelized power cost by 20%. Yet a fivefold increase from the reference value (from 0.65 to 3.25) would decrease power cost by only 12%. Thus, there is a strong incentive to keep the fusion performance from dropping much below the reference values, but not much incentive to improve it dramatically. The reference value of Q_n seems readily attainable, but there is much less certainty about n_d. The latter parameter depends on neutral beam injection, and a great deal of work is required in this area. However, a failure to meet

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*In the reference case, Q_n = 1.0 and M_n = 10. Reference values for other parameters are listed in Table I.

the reference value for n_d could be compensated for by an enhanced value of $Q_{\bar{n}}$, because there is virtually no upper limit to the value of that parameter.

The characteristics of fission blankets are based on neutronics. Although certain simplified assumptions were made in arriving at our reference values, there is little to suggest that the blanket energy multiplication M_n and fissile fuel production rate F will vary significantly from our values. It can be inferred from related calculations that a reduction of F by one third would raise system power costs by about 10%.

One of the most important parameters is $\Delta\Omega$, the fraction of fusion neutrons hitting the blanket. Because the tritium breeding ratio must be kept above 1.0, a reduction in $\Delta\Omega$ must be accompanied by an increase in the fraction of neutrons captured in lithium. Thus, a smaller fraction of the neutrons is available for fissile fuel production. Consequently, fissile fuel production is doubly penalized by a reduction in $\Delta\Omega$. A 33% reduction in $\Delta\Omega$ from our reference value of 0.75 to 0.50 would lower F' by about 60% and decrease M' by 33%. This would be a severe penalty to pay.

Of the three parameters affecting plant performance, the thermal efficiency, n_t, is the most certain and possibly could be expected to exceed our reference value of 0.33.

There is a great deal of uncertainty about the capital cost of a fusion-fission hybrid. Our reference value of $409/MW_t$, based on a very simple formula, amounts to 1.8 times the capital cost of an LWR. A 50% increase in this value would seem reasonable, and our calculations show that this would increase the system power cost by about 10%.

The capacity factor is also a source of great uncertainty. Our reference value of 0.70 is optimistic, especially during the first years of commercial operation. The simultaneous operation of high-technology equipment, required to keep the fusion driver operating, could lead to a high degree of overall unreliability. Although an aggressive development and demonstration program over the next few decades can certainly be expected to improve the reliability of these systems, overall capacity factors of 0.5 or less will probably be characteristic of early commercial hybrids. Although we have not calculated the sensitivity of total power cost to variations in capacity factors, we can estimate the effect by relating it to capital cost, because a reduction in capacity factor can be compensated for with a proportional increase in capital

24

equipment. Under this assumption a reduction in capacity factor from 0.70 to 0.50 would raise total power costs by about 10%.

The combined effect of assuming the pessimistic value for all the parameters discussed would raise total system power costs by about 40%, enough of a difference to discourage any move toward developing the fusion-fission hybrid. However, many of the values quoted for the reference case are already on the pessimistic side, and some are probably close to actual operating conditions. Only a few of the reference parameters, most notably capacity factor and $\Delta\Omega$, are probably optimistic.

VII. INSTITUTIONAL ISSUES

Implementation of a new energy system inevitably depends on a number of legal, political, and social factors. For nuclear energy technologies the most important of these are weapons proliferation and public safety. In the first two sections below, we will examine each of these issues separately. In the third, we will discuss the effect that these and other questions might have on the commercial potential of competing fuel cycles.

A. Proliferation

In recent years, there has been a resurgence of concern in this country over the spread of nuclear weapons. Inevitably, attention has focused on the nuclear proliferation potential in the peaceful nuclear fuel cycle. For the purpose of this discussion, we define proliferation as:

the misuse of peaceful nuclear facilities, skills or materials to assist in the acquisition of a nuclear weapons capability.

Our chief concern is proliferation by national governments.

No nuclear fuel cycle can be proliferation-proof, but some systems are more resistant to this type of abuse than others. In our analysis of proliferation-resistance, we apply three criteria to each fuel cycle. First, we examine the proliferation risks associated with each system. Second, we enumerate the barriers which would be necessary to mitigate these risks. Finally, we examine the ways in which a potential proliferator might be able to misuse the fuel cycle. Having enumerated all of these characteristics, we search for patterns which might make one fuel system more conducive to proliferation than another.

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*The classification of heavy metals by color follows the example of Wohlstetter et al. (Ref. 6).

TABLE VI

PROLIFERATION POTENTIAL OF FUEL CYCLE MATERIALS

- MATERIALS DIRECTLY USABLE (RED)
  PURE HEU (U-235 OR U-233)
  PURE Pu (WEAPON OR REACTOR GRADE)

- MATERIALS REQUIRING SIMPLE CHEMISTRY (ORANGE)
  FRESH FUEL CONTAINING HEU IN Th
 FRESH FUEL CONTAINING Pu IN U

1. Proliferation Risks. There is a wide variety of nuclear material present in nuclear fuel systems. We have classified each material according to the degree of difficulty involved in converting it to nuclear explosives grade (Table VI). Material directly usable for weapons production, such as pure plutonium (Pu) or highly enriched uranium (HEU), is the most dangerous* and labelled "red". An "orange" material is one requiring only simple chemistry for conversion to weapons grade. These would include chemically diluted Pu and HEU, often found in fresh fuels. Any material which requires reprocessing (spent fuel) or enrichment for reduction to weapons grade is classified as "green." Materials requiring enrichment include denatured uranium (DeU), low-enriched uranium (LEU), and natural uranium.

We regard any red or orange material as a significant proliferation risk. However, no proliferation risk is associated with green materials.

A fuel cycle facility is considered a proliferation risk only if it is capable of converting a green mixture to a red or orange one. Only reprocessing and enrichment plants fall into this category. The proliferation risks of fuel cycles are presented schematically in Fig. 12.

2. Proliferation Barriers. A second measure of proliferation potential is the amount of effort necessary to mitigate the risks described above. Three types of barriers to proliferation can be constructed: technical barriers, safeguards, and political arrangements.

26

WASTE
MANAGEMENT

^{238}U
Pu

^{238}U
Pu

REPROCESSING

^{238}U
Pu

REFABRICATION

^{238}U
Pu

^{238}U
Pu

^{238}U
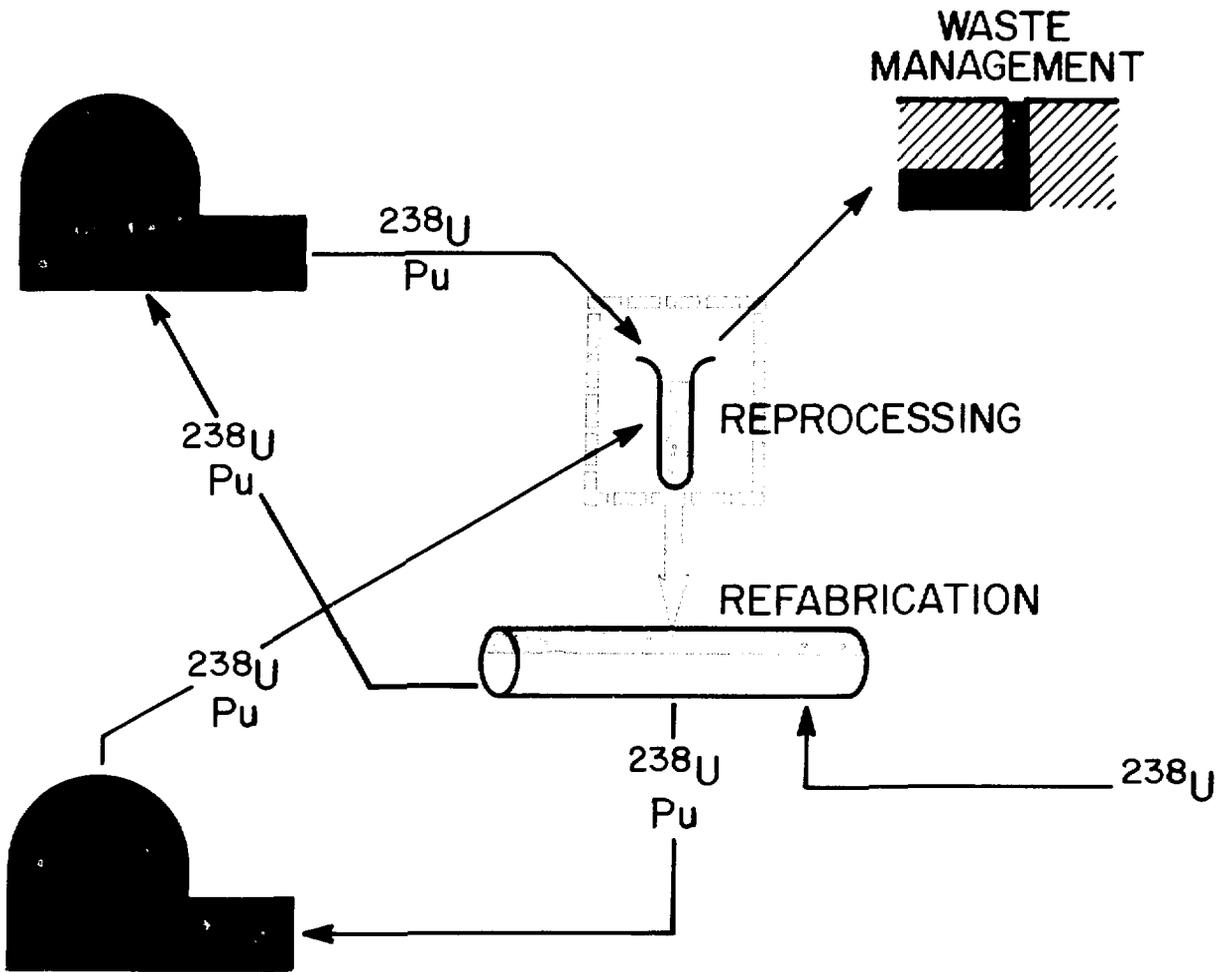
- MATERIALS DIRECTLY USABLE
    PURE HEU (^{235}U OR ^{233}U)
    PURE Pu (WEAPON OR REACTOR GRADE)

- MATERIALS REQUIRING SIMPLE CHEMISTRY
    FRESH FUEL CONTAINING HEU IN Th
    FRESH FUEL CONTAINING Pu IN U

- PROLIFERATION-SENSITIVE TECHNOLOGIES
    REPROCESSING
    ENRICHMENT

Fig. 12.   Proliferation potential of nuclear fuel cycles.

Technical measures are engineering solutions to proliferation risks. We consider only those technical measures that convert red or orange mixtures to green. For HEU this can be accomplished by isotopic denaturing with ^{238}U. Denaturing is not effective for plutonium, however, because any mixture of plutonium isotopes can be used for weapons production. The addition of a radiation barrier would be effective for plutonium because the resulting mixture would require reprocessing.

Safeguards measures include material accountancy and containment/ surveillance activities. Accountancy involves the careful measurement of all sensitive materials in process, in storage, or in transit. Despite the existence of extremely precise on-line monitoring devices, accountancy must be recognized as a necessary, but not sufficient, deterrent to the diversion of sensitive materials.

Accountancy can be effectively supplemented by an array of strategies which we loosely classify as containment/surveillence measures. These types of safeguards include security forces, access monitoring, physical barriers, and a variety of other design features and operating strategies.

To insure the effectiveness of the technical and safeguards barriers, political arrangements must be negotiated. Whether they come in the form of treaties, contracts, or guidelines imposed by nuclear suppliers, these arrangements will encroach on the sovereignty of user nations. Because such measures will be difficult to impose, it would be desirable to develop fuel cycles which require as few of them as possible.

3. Routes to Proliferation. A final test of proliferation vulnerability is the variety of opportunities which the cycle presents to the potential proliferator. These routes to proliferation might include overt actions such as the seizure of a facility or confiscation of sensitive material. Covert means, such as diversion of materials, circumvention of barriers, or misuse of facilities, must also be considered. Finally, there are indirect effects such as the transfer of expertise concerning sensitive technologies.

4. Results. The first step in the analysis is to tabulate the risks, barriers, and routes to proliferation as shown in Tables VII to IX. Obviously, there is a great deal of redundancy in these lists. Even more obvious is the fact that fuel cycles cannot be judged simply by comparing the number of blocks in each colunm. The final analysis requires a critical look at the three tables.

28

TABLE VII

PROLIFERATION RISKS

	LWR	CLASSICAL FBR	FUSION HYBRID
REPROCESSING FACILITIES		███	███
ENRICHMENT FACILITIES	███		
PURE HEU (^{233}U)			
PURE Pu		███	███
HEU (^{233}U) IN THORIUM			
Pu IN URANIUM			

The LWR-OT cycle has the fewest proliferation problems, all of which are associated with enrichment.

The two long-term cycles face an entirely different set of issues, associated with reprocessing facilities and the use of plutonium fuels. A transition from the LWR-OT cycle to one of the long-term options would represent a qualitative increase in proliferation potential.

However, there is clearly no substantial difference between the classical FBR cycle and the hybrid system with respect to their proliferation potential. This is not a surprising result in view of the similarity of their fuel cycles.

B. Health, Safety, and the Environment

Large energy facilities affect the human environment in two ways: by consuming valuable resources and by producing toxic substances. In the case of nuclear facilities the toxicants can be either chemical or radiological.

1. Resource requirements. The most important resources used in the nuclear fuel cycle are land, water, and minerals.

TABLE VIII

PROLIFERATION BARRIERS

	LWR	CLASSICAL FBR	FUSION HYBRID
TECHNICAL: ISOTOPIC DENATURING OF ^{233}U			
RADIATION BARRIER FOR Pu		■	■ o
SAFEGUARDS: ACCOUNTANCY OF ^{233}U			
OF Pu		■	■
CONTAINMENT/SURVEILLANCE OF REPROCESSING		■	■
OF ENRICHMENT	■		
INSTITUTIONAL: CONTROL/OVERSIGHT OF REPROCESSING		■	■
OF ENRICHMENT	■		
VERIFICATION OF DENATURING			
OF Pu RADIATION BARRIER		■	■
CONTROL OF REPROCESSING TECHNOLOGY TRANSFER			
CONTROL OF ENRICHMENT TECHNOLOGY TRANSFER	■		

Land requirements of the LWR-OT and classical FBR cycles do not differ significantly.[7] Because the hybrid supports so many LWR's, land requirements of the hybrid system cannot vary markedly from those of the LWR-OT cycle, even if the land requirements of the hybrid itself were usually high.

Water requirements of electrical energy systems are roughly proportional to the power produced. Differences in efficiencies of reactors and fuel cycle facilities can cause some variations in water consumption. However, it is not likely that any of the fuel cycles considered in this report will have a sizable advantage over the others with respect to water requirements.

Material requirements of the hybrid are probably comparable to those of the other cycles, although such a claim is difficult to substantiate in the absence of a specific design. As with the land requirements, any outstanding material requirements of the hybrid would be offset by the fact that so few of them are required.

TABLE IX

ROUTES TO PROLIFERATION

	LWR	CLASSICAL FBR	FUSION HYBRID
CONFISCATION OR DIVERSION OF ^{233}U			
OF Pu		■	■
HOST COUNTRY SEIZURE OF REPROCESSING		■	■
ENRICHMENT	■		
COVERT CIRCUMVENTION OF ^{233}U DENATURING			
COVERT CIRCUMVENTION OF Pu RADIATION BARRIER		■	■
COVERT MISUSE OF ENRICHMENT FACILITY TO PRODUCE HEU	■		
TRANSFER OF REPROCESSING EXPERTISE		■	■
TRANSFER OF ENRICHMENT EXPERTISE	■		

2. Chemical toxicants. The problem of chemical pollution is a relatively minor issue for nuclear fuel cycles, especially for systems which do not require much mining and milling of uranium. In a separate study[1] we concluded that the classical FBR cycle has a marginal advantage over the LWR-OT cycle in this respect.

Because the fuel cycle facilities associated with the hybrid are identical in type to those of the classical FBR, chemical pollution from the two cycles is not likely to differ by much.

3. Radiological Hazards. The health effects of radioactive releases during normal operation of nuclear facilities are not known with great certainty. Levels of emissions can vary from one plant to another. Furthermore, transport of the toxicants into the human environment depends on local climate and geology. Finally, the effects of low-level radiation exposure are not well understood. Consequently, the standards for operation of nuclear facilities are, and should be, based on conservative estimates of health effects.

Several investigators[8-11] have tried to assess the health effects of the total nuclear fuel cycle. Although these studies addressed different fuel cycles and used different methodologies, they all reached similar conclusions. These and other studies concluded that nuclear facilities can be routinely operated with no significant radiological hazard to the public.

A recent study[12] identified reprocessing plants and uranium mines and mills as the principal sources of public exposure to radioactivity. This study concluded that the risks associated with reprocessing are outweighed by the resulting reduction in mining and milling activity. In a comparison of fuel cycles, this result tend to favor the two long-term options over the LWR-OT cycle.

Operation of the hybrid requires routine handling of large quantities of tritium, a radioactive gas that is highly susceptible to release and readily transports into the human body. Systems for handling tritium would have to be carefully engineered to minimize releases.

In addition to hazards during normal operation, one must also be concerned with reactor accidents. In a separate study[1] we summarized the results from engineering studies of the probability and consequences of accidents for both the LWR[13] and the liquid metal fast breeder reactor LMFBR.[14] The risks, which in both cases are dominated by low-probability, high-consequence accidents, were found to be comparable for the two reactors.[15]

No detailed risk analyses have yet been performed for the fusion-fission hybrid. However, it is possible to compare some of the intrinsic safety characteristics of hybrids with those of conventional reactors.

For instance, the inventory of short-lived radionuclides is comparable in all reactors of similar power, including the hybrid. In the event of a meltdown, the release of these fission products would be the principal public health problem. These short-lived isotopes also dominate the requirements for emergency cooling. In the case of the hybrid, the fact that they are spread out over the large volume of the blanket means that the heat may be more easily dissipated. On the other hand, this same large volume all but precludes the use of natural circulation cooling systems such as are used in the LMFBR.

In the event of an emergency, it would be much simpler to shut down a hybrid reactor than a fission reactor. The hybrid will cease to operate if

any one of several high-technology components is defused, whereas the fission reactors will continue to generate power unless an active control system can be inserted. In addition, the fissile inventory of a hybrid is less likely to reform itself into a critical mass after meltdown.

A peculiar safety hazard associated with the hybrid is the potential disruption of operational and emergency equipment by the accidental release of cryogenic potential energy (liquid nitrogen, helium, and tritium), chemical energy (lithium, sodium, and tritium fires), and magnetic energy.

4. Summary. The health and safety aspects of the LWR-OT cycle are reasonably well understood. Impacts of the classical FBR cycle can be inferred from experience with fuel cycle facilities and with demonstration-scale reactors. The same can be said for all aspects of the hybrid cycle, with the exception of the reactor itself. It is not possible to determine at this time whether normal emissions from the hybrid can meet the standards currently set for other nuclear facilities. Furthermore, we cannot determine with any certainty whether the hybrid reactor is as safe as the LWR and the LMFBR. More detailed study may reveal that the hybrid is preferable to conventional fission reactors. However, as long as this uncertainty about the hybrid persists, the health and safety issue will favor the more familiar classical FBR cycle as the long-term source of nuclear energy.

C.   Commercialization

Bringing a new technology successfully to market requires a complicated interplay of many actors. We can understand this process by examining the factors which influence each of the decisionmakers involved.

The current framework for commercializing nuclear technologies involves five types of decisions:

(1) the expenditure of federal funds for research, development, and demonstration (RD&D);

(2) industrial commitment to manufacture the reactors and operate fuel facilities;

(3) a decision on the part of utilities, with approval from state regulatory commissions, to operate the reactors;

(4) licensing of all facilities by the Nuclear Regulatory Commission (NRC); and

(5) public acceptance of all the facilities.

Recent experience with the LWR-OT cycle has led some analysts[16] to wonder about the viability of nuclear energy under the current system. Among the options under consideration is a greater role on the part of the federal government in manufacturing and operating new technologies. In our comparison of fuel cycles, we will examine their commercial potential in the current framework of the nuclear industry and in the scenario of increased government involvement.

The LWR-OT cycle has been in operation for two decades, and we will assume for the purpose of this discussion that it will retain its commercial status. Consequently, we will focus on a comparison of the commercial potential of the classical FBR and fusion-fission hybrid cycles by examining how each cycle would be perceived by the decisionmakers listed above.

1. Research, Development, and Demonstration. The classical FBR cycle requires the commercialization of a breeder reactor. The liquid metal fast breeder reactor (LMFBR) has achieved an advanced state of development as a result of massive RD&D programs in the United States, France, Germany, Britain, and the Soviet Union. Research on fabrication and reprocessing of LMFBR fuels has also progressed at a satisfactory pace. Barring a major shift of emphasis, the momentum of this worldwide program will soon bring the LMFBR and the plutonium fuel cycle to commercial status.

A demonstration program for the fusion-fission hybrid would involve a large new investment by the federal government. Such a program could be justified in part as a means of paving the way for pure fusion reactors, but the main impetus would have to come from a real or perceived advantage of the hybrid over the FBR as a breeder of fissile fuel.

2. Marketing the Technologies. In view of industry's disappointing experience with nuclear energy, it will be difficult to obtain a commitment to market any new nuclear technology. The fast breeder reactor has an advantage in this regard because it represents an evolutionary departure from current LWR technology. By contrast, the hybrid is a radically new concept. A further deterrent is the fact that relatively few hybrids would be required to fuel an ambitious nuclear buildup. This limited market, coupled with the extreme capital intensity of the technology, would make it a poor investment for industrial firms.

On the other hand, if the government were to become the manufacturer of new reactors, the fact that few hybrids are required might be perceived as a point in its favor.

34

3. Operation of the Reactors. In the years to come electric utility companies are likely to be more reluctant to purchase nuclear reactors. Rising capital costs, long lead times, uncertain inflationary trends, and high interest rates will tend to favor other less capital-intensive methods of generating power.

Given a choice between the LMFBR and the fusion-fission hybrid, most utility companies would choose the former. The greater capital intensity of the hybrid, the increased complexity of maintenance and operation, and its susceptibility to frequent unscheduled outages would make the hybrid a very unattractive option. It is also questionable whether utilities and their state regulatory commissions would want to operate facilities that produce large quantities of fissile fuel and small amounts of electricity. Utility companies would clearly favor the fast breeder reactor.

On the other hand, in a scenario where the federal government operates the breeder reactors, the fusion-fission hybrid would have several advantages over the FBR. First, because fewer hybrids would be required, the federal government's investment would be considerably smaller if it chose hybrids instead of the FBR. Second, because the hybrids produce very little net electricity, the government would not find itself in competition with private utility companies. Hybrid fuel factories could be operated in a manner analogous to enrichment plants, a role to which the government is quite accustomed.

4. Nuclear Facility Licensing. Regulations and procedures for the licensing of nuclear reactors and fuel cycle facilities are always subject to change. Consequently the licensability of fuel cycles should not be compared on the basis of the detailed regulatory guidelines in place at this time. However, the standards for licensing, as stated in the Code of Federal Regulations,[17] will probably remain the same. The NRC will have to determine how each fuel cycle facility affects (a) the common defense and security and (b) the health and safety of the public.

The issue of nuclear weapons proliferation and its implications for national security is likely to be a major factor in licensing decisions. The significant increase in proliferation potential posed by both of the long-term cycles will make them more difficult to license than the current LWR-OT cycle. However, because the two long-term cycles are nearly identical with

35

respect to proliferation, there is no reason to believe that either one would be more licensable on the grounds of national security.

The principal health and safety problems of the nuclear fuel cycle are the safety of reactors and the long-term integrity of nuclear waste repositories. The principal difference between the two fuel cycles in this area is the uncertainty about the safety of the hybrid reactor. However, because so few hybrid reactors would be required and because they generate so little electricity, their safety problems might be offset by remote siting. We believe it is premature to compare the health and safety aspects of the classical FBR and hybrid cycles.

In summary, we do not have any evidence to suggest that either of these fuel cycles would be more licensable than the other.

5. Public Acceptance. Active public involvement in technological issues is generally mobilized only at times when major changes are being debated. A transition from the current LWR-OT cycle to one or both of the long-term options might be an occasion for intense public participation. Citizens would have to grapple with the implications of "breeder" reactors, "plutonium" fuels, and "reprocessing."

It is not likely, however, that public initiative would distinguish between the classical FBR and the fusion-fission hybrid cycle.

6. Summary. The future of nuclear power rests in the hands of a diverse group of decisionmakers whose motives and methods vary greatly.

In some respects, the two long-term cycles are similar. Each would probably be equally likely to win licensing approval and public acceptance.

In other respects, the advantage could belong to either cycle, depending on who the decisionmaker is. For instance, if the next generation of reactors is to be manufactured by private industry and operated by utilities, the fast breeder reactor cycle would be preferred. If, on the other hand, the federal government becomes the manufacturer and operator of fissile breeders, the hybrid would have the advantage.

The crucial difference between these two cycles is one of readiness. Whereas the fast breeder will probably be a commercial technology in the near future, the fusion-fission hybrid has yet to be proven scientifically feasible. A decision to commit federal funds for the demonstration and commercialization of the hybrid would have to be based on a conviction that the hybrid is vastly superior to the LMFBR as a breeder of fissile fuel.

36

Although the hybrid is indeed superior in some respects, it also has some drawbacks. Furthermore, as is always the case with an untested concept, there is the possibility that unforeseen problems will emerge as the technology becomes better understood.

In the face of an already commercialized fast breeder reactor, there is not sufficient incentive, in our opinion, to demonstrate and commercialize the fusion-fission hybrid.

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