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Perspective on the Fusion-Fission Energy Concept

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PERSPECTIVE ON THE FUSION-FISSION ENERGY CONCEPT

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ABSTRACT

A concept which has potential for near-term application in the electric power sector of our energy economy is combining fusion and fission technology. The fusion-fission system, called a hybrid, is distinguished from its pure fusion counterpart by incorporation of fertile materials (uranium or thorium) in the blanket region of a fusion machine.

The neutrons produced by the fusion process can be used to generate energy through fission events in the blanket or produce fuel for fission reactors through capture events in the fertile material. The performance requirements of the fusion component of hybrids is perceived as being less stringent than those for pure fusion electric power plants. The performance requirements for the fission component of hybrids is perceived as having been demonstrated or could be demonstrated with a modest investment of research and development funds. This paper presents our insights and observations of this concept in the context of why and where it might fit into the picture of meeting our future energy needs.

I. INTRODUCTION

Energy is vitally important to the economy of the United States (U.S.) and we are running out of critical resources to supply the energy needed to support our economy. The electric utility industry is a major user of primary resources. Since electric utility companies are committed to providing reliable electric service and to deliver this service as cheaply as possible they are justifiably concerned with depletion of primary resources.

There are many forecasts of electric power generation which indicate a short-fall between supply and demand near the turn of the century. The question is, what energy technology can be developed in time to fill this gap? A concept which has potential for electric power application early in the twentieth century is combining fusion and fission technology. The fusion-fission system, called a hybrid,* could produce electric power directly, or generate fuel for existing nuclear power plants (Light Water Reactors) or generate both electric power and fuel.

In this paper we briefly describe the principal features of the pure fusion and hybrid processes and attempt to show where hybrids might fit in the energy picture. Performance-cost targets which the hybrid must meet to compete with other major electrical generation technologies are briefly outlines. Currently, there is much concern

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*Hereafter we simply refer to fusion-fission (hybrid) systems as hybrid systems or hybrids.

about fission technology in the context of weapons proliferation. The hybrid concept is related to the nonproliferation scenarios being considered for fission technology. Major near-term technological requirements for hybrid systems are identified. In the summary we offer our judgments regarding the development of this concept.

II. THE HYBRID CONCEPT

The common feature of the fusion and fission processes is that they both generate neutrons. The distinguishing feature is their number and the energy liberated in the process.

A. Fusion Process

The fusion process is shown in Figure 1. Atoms of deuterium and tritium are heated and confined in a plasma where they fuse and split into helium atoms and neutrons, as shown in Equation 1.

$$ {}^{2}_{1}\mathrm{D} + {}^{3}_{1}\mathrm{T} + \text{Energy} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + \text{Energy} \qquad (1) $$

In doing so, about 17.6 MeV of energy is released. The major portion of the energy released in the reaction (Energy on the right side of Equation 1) is in the energy of the neutron (n), about 14 MeV. This neutron travels to the blanket region surrounding the plasma where it eventually strikes a lithium atom, deposits its energy, and creates tritium in the process through these reactions

$$ \begin{aligned} {}^{7}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n}\ (\text{fast}) &\longrightarrow {}^{3}_{1}\mathrm{T} + {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}\ (\text{slow}) \\ {}^{6}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n}\ (\text{slow}) &\longrightarrow {}^{3}_{1}\mathrm{T} + {}^{4}_{2}\mathrm{He} + 4.8\ \text{MeV} \end{aligned} \qquad (2) $$

The first reaction in Equation 2 occurs with fast neutrons (i.e., MeV range) whereas the other reaction occurs when the neutron energy is substantially degraded from 14 MeV. The tritium produced by the reactions shown in Equation 2 is extracted and used to refuel the reactor plasma.

B. Fusion-Fission (Hybrids) Process

The hybrid is distinguished from its pure fusion counterpart by incorporation of fertile material (uranium or thorium) in the blanket region of a fusion reactor. The fusion-fission process is depicted in Figure 2. The 14 MeV neutron produced in the plasma region travels to the blanket where it becomes absorbed by the fertile material and deposits energy. Subsequent reactions, neutron reemission, fission or capture, can take place which depends upon the energy of the absorbed neutron. If the neutron energy is high enough the neutron multiplying (Equation 3) and fission (Equation 4) reactions are dominant.

$$ \mathrm{n} + \mathrm{U}\ (\text{of Th}) \longrightarrow 2 \text{ or } 3 \text{ neutrons} \qquad (3) $$

$$ \mathrm{n} + \mathrm{U}\ (\text{or Th}) \longrightarrow 2 \text{ Fission Fragments} + \text{multiple neutrons} \qquad (4) $$

About 180 MeV of energy is released in the fission reaction and more neutrons are released. If the neutron energy is degraded below ∿2 MeV, the principal absorption reaction is capture. The capture reactions are

$$ \begin{aligned} {}^{1}_{0}\mathrm{n} + {}^{238}_{92}\mathrm{U} &\longrightarrow {}^{239}_{92}\mathrm{U} \xrightarrow{\beta^-} {}^{239}_{93}\mathrm{Np} \xrightarrow{\beta^-} {}^{239}_{94}\mathrm{Pu} \\ {}^{1}_{0}\mathrm{n} + {}^{232}_{90}\mathrm{Th} &\longrightarrow {}^{233}_{90}\mathrm{Th} \xrightarrow{\beta^-} {}^{233}_{91}\mathrm{Pu} \xrightarrow{\beta^-} {}^{233}_{92}\mathrm{U} \end{aligned} \qquad (5) $$

The end product of these reactions are ${}^{239}\mathrm{Pu}$ and ${}^{233}\mathrm{U}$. These isotopes are both fissile materials thereby condidate fuels for fission power plants.

Comparing the fusion process with the process in a hybrid shows that more energy is released in the hybrid when fission occurs. The fusion process yields ∿18 MeV of energy whereas fission in the hybrid blanket yields ∿180 MeV, roughly ten times more energy release. In the high energy reemission and fission processes, additional neutrons are also released. Thus, in the hybrid both energy and neutron multiplication take place which are considered desirable features for reaction applications.

C. Why Hybrids?

There are two principal reasons why hybrids appear interesting. The first is that the fusion plasma requirements for hybrids are generally less stringent than those for pure fusion power plants. The second reason is that the hybrid appears to be able to play multiple roles in the nuclear power economy.

A projection of electric generation mix,(1) shown in Figure 3, is used here to put the hybrid concept in perspective of the potential roles it could play. With those technologies shown on the right side of Figure 3, this projection predicts a potential shortfall between electricity supply and demand shortly after the year 2000. One of the interests in hybrids stem from the thought that an electric power producing hybrid might be developed in time to ease or eliminate this potential shortfall.

The middle of Figure 3 illustrates the sensitivity of nuclear power generation to estimates of uranium supply. The shaded area labeled IV shows the nuclear contribution based upon a uranium supply limit of 1.8 million tons of U_3O_8 and where we do not reprocess and recycle fissile material. The shaded area labeled III shown the added contribution to electricity supply if the uranium supply limit is 3.5 million tons of U_3O_8 and spent fuel is reprocessed to recover and recycle fissile material (i.e., plutonium). Because of the uncertainty in uranium supply, electric utility companies owning nuclear power plants are interested in concepts, such as the hybrid, which can produce fissile fuel to run these power plants. With an additional supply of fissile material the nuclear increment might grow substantially above that shown in Figure 3. Hence, utility companies having (or expecting to have) nuclear power plants are interested in the concept of a hybrid as a fuel factory for fission reactors.

The hybrid concept is also looked upon as a step along the pathway to pure fusion power. It is conceivable that many uncertainties in plasma physics, plasma engineering, and blanket engineering performance of pure fusion systems could be resolved through the development of hybrids. Thus, as shown in Figure 4, hybrids could be a step on the road to achieving the benefits of pure fusion technology.

III. ECONOMIC AND NONPROLIFERATION PERSPECTIVES

In this section we attempt to put the hybrid concept in perspective of hybrids competing in the electric energy marketplace and in relation to the nonproliferation considerations of fission power systems.

A. Economic Perspective

We utilize the results of previous studies(2,3) to develop a perspective on the performance-cost targets for hybrids. In these studies, the capitalized costs for hybrids which allow the hybrid to compete with alternatives were computed for systems producing varying degrees of fissile fuel and electricity for sale. Thus, the key parameters in these analyses are the hybrid:

- capital cost
- fuel production rates
- electrical energy production

The alternative electric generation plants included: fossil power plants, LWR's Liquid Metal Fast Breeder Reactors (LMFBRs), High Temperature Gas Cooled Reactors (HTGRs), and pure fusion power plants. The base cases included hybrids along with fossil and LWR power plants. Sensitivity cases were run with and without the other reactor types. We have extracted a limited amount of the data in References 2 and 3 to provide a perspective. We refer the reader to these references for additional detail.

In Figures 5 through 7 we show the capitalized cost for a hybrid producing varying amounts of fissile material which allows them to compete in the U.S. electric generation economy. The capital cost of a LWR is shown as a point of reference. These data can be thought of as giving the designers of hybrids some guidance on plant performance projections necessary to be competitive. We first show (in Figures 5 and 6) the results where the only plants in the electric power economy are fossil, LWR, and hybrid plants. The effect of having LMFBRs and pure fusion power plants in the economy is shown in Figure 7.

The case for a hybrid which produces only fissile material for sale to LWRs is shown in Figure 5. The hybrid produces enough power however to break even, i.e., meet its own needs. A production rate of 1.0 kg/MW$_{th}$ supports approximately five (5) LWR's. These results show that the capital cost of a hybrid producing less than $\sim$1.3 kg/MW$_t$ must be less than the capital cost of a LWR. For production rates above this, the hybrid plant could cost more than the capital cost of a LWR. It's questionable that a hybrid could be built for less capital cost than a LWR. Thus, the performance target area for fuel producing hybrids which breakeven on power is the shaded area. We point out, however, that the location of this curve vertically in the figure is sensitive to many input data, particularly electrical growth rate and prices for U_3O_8 and these results are a year to two out of date. An off-line fuel producing hybrid is of high interest to LWR power plant owners because it doesn't have to be hooked to the grid and be dependent on the many utility operations variables for plants which are. Therefore, a comprehensive and thorough analyses of this type of system is needed to put this hybrid concept in better perspective on filling this role in the electric generation economy.

The allowable capitalized costs for a hybrid which produces both electricity and fissile fuel for sale is shown in Figure 6. In this situation the costs range from near LWR capital cost for a hybrid producing no fissile material for sale to about 2.5 times LWR capital cost for a hybrid producing 1.5 kg/MW$_t$. The effect of having the LMFBR and the pure fusion reactor competing with the hybrid is shown in Figure 7. As shown, the capital cost of a hybrid must be cheaper if it's to compete with LMFBRs amd pure fusion power plants.

It's clear from these results that a dual purpose (fuel and electricity production) hybrid might be an economically viable concept in the electric generation marketplace. The case for the fuel producing hybrid needs further study.

B. Nonproliferation Perspective

There is concern that reprocessing spent LWR fuel based on the current solvent extraction process involving isolation of plutonium might allow the diversion of plutonium for weapons purposes. The U.S. is stressing assessment and development programs for alternative fuel cycles which might reduce or eliminate risk of nuclear weapons proliferation. The U.S. nonproliferation concerns have resulted in the Department of Energy (DOE) Nonproliferation Alternative Systems

Assessment Program (NASAP)$^{(4)}$ and the International Fuel Cycle Evaluation (INFCE). Approximately forty nations are participating in the INFCE.

To put hybrids in context with nonproliferation policy, we choose scenarios of not reprocessing spent fuel and reprocessing spent fuel to recover and recycle fissile materials in fission reactors. In the reprocessing scenario, we examine two cases, first where reprocessing is restricted to recovery and recycle of denatured ^{233}U in fission reactors and second; where plutonium is recovered and recycled in fission reactors.

1. No Reprocessing Scenario

The current once-through LWR fuel cycle is shown in Figure 8. The spent LWR fuel is shown going to storage (SURF) where it stays until such time that a decision is made to dispose of it or recycle. We use the dashed arrow to indicate the uncertainty in future decisions, whether recycling is in the national interest.

In the no-reprocessing scenario, the hybrid role is limited to producing power for sale. The hybrid fuel cycle analagous to the once-through LWR cycle is shown in Figure 9. The depleted uranium, which comes from the tails of enriching the ^{235}U content of natural uranium, is used as blanket material for a hybrid. The blanket is irradiated, the uranium fissions, and power is generated. The spent blanket is discharged and stored awaiting ultimate disposition. Natural uranium and/or thorium could also be used as a source of feed for fabricating hybrid blankets.

A concept which has only recently been briefly studied$^{(5)}$, based upon the no-reprocessing scenario, is the "refresh cycle". This is shown in Figure 10. Natural thorium is mined and refined to produce thorium for fabricating a thorium blanket for the hybrid. The blanket is irradiated in the hybrid where neutrons are captured in ^{232}Th to produce ^{233}U. The bred 233 blanket material is inserted in High Temperature Gas Cooled (HTGR) fission reactor to produce power. After the ^{233}U is depleted in the HTGR it is sent back to the hybrid to be "refreshed" in ^{233}U. Upon refreshing, the fuel is again used in the HTGR for power production. After this cycle, the spent fuel is stored and ultimately disposed of.

The concept of refreshing spent LWR fuel in a hybrid reactor has also been studied briefly.$^{(6)}$ In the concept studied, reprocessing and refabrication of the U-Pu fraction was considered.

None of the above concepts have been studied to any extent. Hence assessments of their technical feasibility and/or economic viability are premature at this point in time.

2. Restricted Reprocessing - Denatured ^{233}U

Denaturing a fissile isotope such as ^{233}U means diluting it with another isotope of uranium to the extent that a nuclear weapon cannot be made directly from the material. In the case of the fissile uranium isotopes (^{235}U and ^{233}U) ^{238}U serves as the diluent. No corresponding isotope of plutonium can denature the fissile isotopes of plutonium (^{239}Pu and ^{241}Pu).

This scenario assumes uranium (rather the fissile component, ^{235}U) is in short supply. The limitation of ^{235}U supply can be alleviated through utilization of thorium to generate ^{233}U (which is denatured) and thereby extend the supply of fissile material for fission reactors. The LWR thorium cycle is shown in Figure 11. Raw materials bearing thorium are refined to produce ThO_2 which is mixed with enriched UO_2 to fabricate ThO_2-UO_2 fuel for an LWR. The spent fuel is reprocessed to recover denatured ^{233}U which is refabricated into new fuel. Since this is not a breeder cycle, an external source of ^{233}U is needed to sustain the system and allow it to grow. The hybrid could be the external source.

The hybrid concept based on this scenario is shown in Figure 12. Mined thorium is refined and a thorium blanket for the hybrid is fabricated. Irradiating this blanket in the hybrids builds in ^{233}U which is reprocessed and denatured (^{238}U added during reprocessing). The denatured uranium is mixed with thorium during fabrication to produce LWR fuel. Once the spent fuel is discharged from the LWR, the steps shown in Figure 11 would be followed. This concept has not been examined to date.

3. Reprocessing for Plutonium Utilization

Since plutonium cannot be denatured, other means must be found to make plutonium proliferation resistant. The technical and institutional fixes being examined in NASAP and INFCE include

- Keeping the plutonium and uranium together at all times (e.g., coprocessed U-Pu)
- Making the plutonium fuel highly radioactive (e.g., having highly radioactive materials in the fuel)
- Restricting plutonium to fuel cycle centers

All of these are variants on the once-through cycle depicted in Figure 1 where spent fuel would be reprocessed and recycled rather than disposing of it. The technical modifications listed in the first two bullets above would be made as a part of reprocessing and/or refabrication. The fuel cycle center would probably contain both the reprocessing plant and the refabrication plant, and possibly those reactors using the plutonium fuel. The plutonium produced in hybrid blankets would probably be subject to the same restrictions as that produced in fission reactor fuels.

IV. NEAR-TERM TECHNOLOGY REQUIREMENTS

For near-term application, the technology requirements for a hybrid are dictated by the development pathway for pure fusion because hybrids should be able to piggyback the fuel cycle technology development for fission reactors. The hypothetical pathways to reach commercial application for pure fusion and hybrids are shown in Figure 13. It is presently perceived that at some point along the pure fusion pathway that there is a jumping-off point for hybrids and that commercial application for a hybrid could be attained sooner than for pure fusion. To put this in better perspective, we briefly compare the technology requirements for pure fusion and hybrid Reactors.

Figure 14 was constructed to aid the discussion of the technology requirements. Basically, certain properties of the plasma must be achieved and to achieve these requires confining forces and other energy inputs. Plasma confinement is accomplished by using one of two methods, either magnetic or inertial forces. The high temperature plasma requirement dictates that the plasma be restrained from contact with the vacuum wall which would cool the plasma and probably damage the wall. Strong magnetic fields are used to exert pressure on the plasma and keep the plasma away from the wall in magnetic confinement. In inertial confinement, an incident pulse of high energy intensity (such as from a laser) is used for compression. The power output from any power plant must exceed the input to be viable. The engineering of the vacuum wall and the blanket are important factors in assuring the desired power output is attained from fusion and hybrid plants. Much of the information given below was extracted from References 7-11.

A. Plasma Requirements

The required plasma properties for reactors are given in Table 1. The property $n\tau$ is the product of the plasma density (n) and the plasma confinement time (τ). For a fusion reactor this must be $\sim 10^{14}$ seconds/cm^3. The hybrid can get by with around 10^{13} which is near the current state-of-the-art. The required ion temperature for fusion is also higher than for a hybrid and again the current state-of-the-art is coming close to meeting the hybrid requirement.

B. Confinement Force Requirements

The principal confinement force requirements are listed in Table 2. For magnetic confinement the field strength exceeds 5 tesla for fusion, is approximately 4 for hybrids, and the current status is nearer 3. For inertial confinement the hybrid requirements are near to being met whereas pure fusion requires an order of magnitude improvement.

C. Power Input Requirements

The power input requirements are listed in Table 3. For magnetic systems, though the hybrid requirements are less than those for fusion, both are substantially larger than the current state-of-the-art. For inertial confinement, the input power for a hybrid reactor is an order of magnitude less than for a fusion reactor. The hybrid requirements are close to being met with current state-of-the-art. The rep rate is the rate at which the compression energy must be delivered. Both the fusion and hybrid requirements are high compared to the current state-of-the-art.

D. Power Output Requirements

The output power requirements are given in Table 4. In a fusion reactor the power is produced in the plasma whereas in the hybrid the power is produced in the blanket. These numbers describe the basic difference between a fusion reactor and a hybrid reactor, namely the power density in the blanket. However, as shown, useful power has not been achieved in either case.

E. Vacuum Wall and Blanket Engineering Aspects

The differences cited in Table 4, on where the power is produced, translate into differences in engineering problems in the vacuum wall and the blanket. The power produced in the plasma of a fusion reactor must be deposited in the blanket for subsequent recovery. To accomplish this means transferring the power to and through the vacuum wall. This high power level at the vacuum wall impairs the structural integrity of the wall. As shown in Table 5, the neutron wall loading at the first vacuum wall is about twice as high for a fusion reactor as it is for a hybrid reactor. However, since the power density in the blanket is higher in the hybrid the blanket cooling requirements are correspondingly higher (however, well within the technology of fission reactors).

Considering the near-term requirements of hybrid reactors we look to using the technology developed in fission research and development programs wherever possible in hybrid applications. This means we would select blanket materials which have (or will have when needed) established technical bases (for the performance of fuels, coolants, and structural materials used in the hybrid blanket). In addition, the uranium and/or thorium blankets would be based on existing technology for fabrication, and reprocessing of blankets. Otherwise, if substantial new research and development investments are needed for the hybrid blanket, then the timeliness and cost incentives of employing the concept commercially are comprised.

V. SUMMARY AND CONCLUSIONS

The concept of the hybrid has been outlined and reasons why this concept is interesting are given. The interest stems mainly from fuel supply uncertainties for fission reactors and the possiblity that hybrids might be a step along the pathway to pure fusion. We described the technological requirement differences between pure fusion and hybrid reactors. Indeed it does appear that the hybrid requirements are less than those for pure fusion and are attainable in the near-future. On the basis of looking ahead to where magnetic and inertial confinement technology is going we speculate that the jumping off point might be somewhere between 1983 and 1985 as shown in Figure 15. Accepting this, then when could we expect commerical application of the hybrid? The phases of research and development leading to commercializing a new technology(12) are shown in Figure 16. This figure illustrates that about 25 years are needed following scientific feasibility to arrive at a commercial plant. Assuming the jumping off point in Figure 16 is 1985, this would say that a commercial hybrid plant could be expected in the year 2010. If indeed, as shown in Figure 1, if the shortfall starts in 2000 and the hybrid is looked upon as being thrown in the breach to meet this need, then clearly the study and development of hybrids warrants acceleration.

To date there has not been enough investment in hybrid research and development to be able to reliably ascertain the technical feasibility and the economic viability of the concept. This leads us to the conclusion that hybrids have not received proper emphasis in planning future U.S. energy systems.

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TABLE 1. Required Plasma Properties for Reactors

	Fusion	Hybrid	Current State
$n\tau$ (Seconds/cm^3)	$\gtrsim 10^{14}$	$\sim 10^{13}$	$\sim 10^{13}$
Ion Temperature (keV)	$\gtrsim 10$	5-10	< 5

TABLE 2. Confinement Force Requirements

	Fusion	Hybrid	Current State
Magnetic			
Magnetic Field Strength (Tesla)	>5	~ 4	~ 3
Inertial			
Energy on Target (MJ)	>1	>0.1	<0.1

TABLE 3. Power Input Requirements

	Fusion	Hybrid	Current State
Magnetic			
Input Power (MW)	~ 500	~ 400	5
Pulse Length (sec)	$\sim 10^4$	$\sim 10^3$	<1
Inertial			
Input-Power (TW)	>1000	>100	<100
Rep Rate (H_z)	1-10	~ 1	$\sim 10^{-3}$

TABLE 4. Power Output Requirements

Power Produced	Fusion	Hybrid	Current State
Plasma	~ 3000	~ 300	0
Blanket	~ 500	~ 3200	0

TABLE 5. Vacuum Wall and Blanket Engineering Aspects

	Fusion	Hybrid
Structural Integrity	High	Moderate
- Neutron Wall Loading (MW/m^2)	~ 5	~ 2
Blanket Cooling	Moderate	High

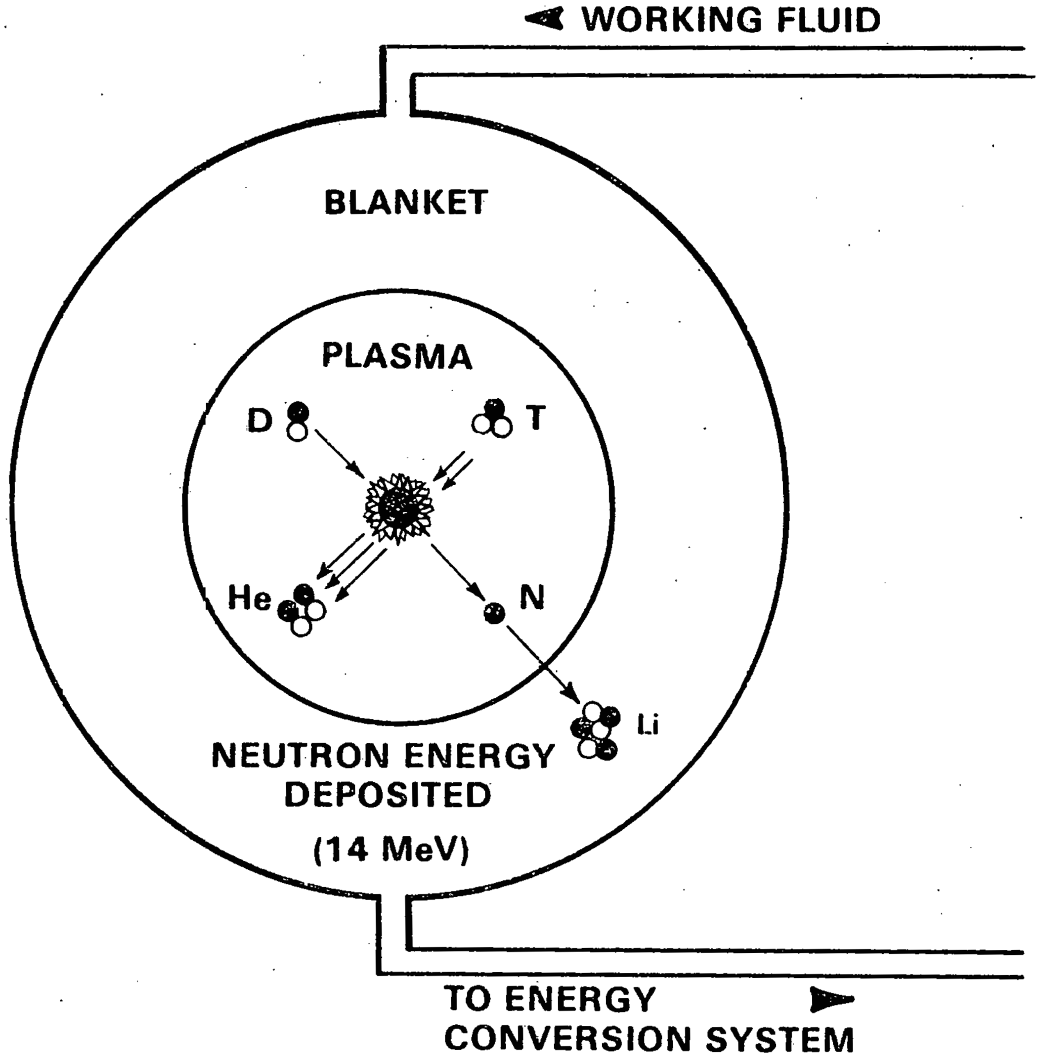

FIGURE 1

FIGURE 1. Fusion Process

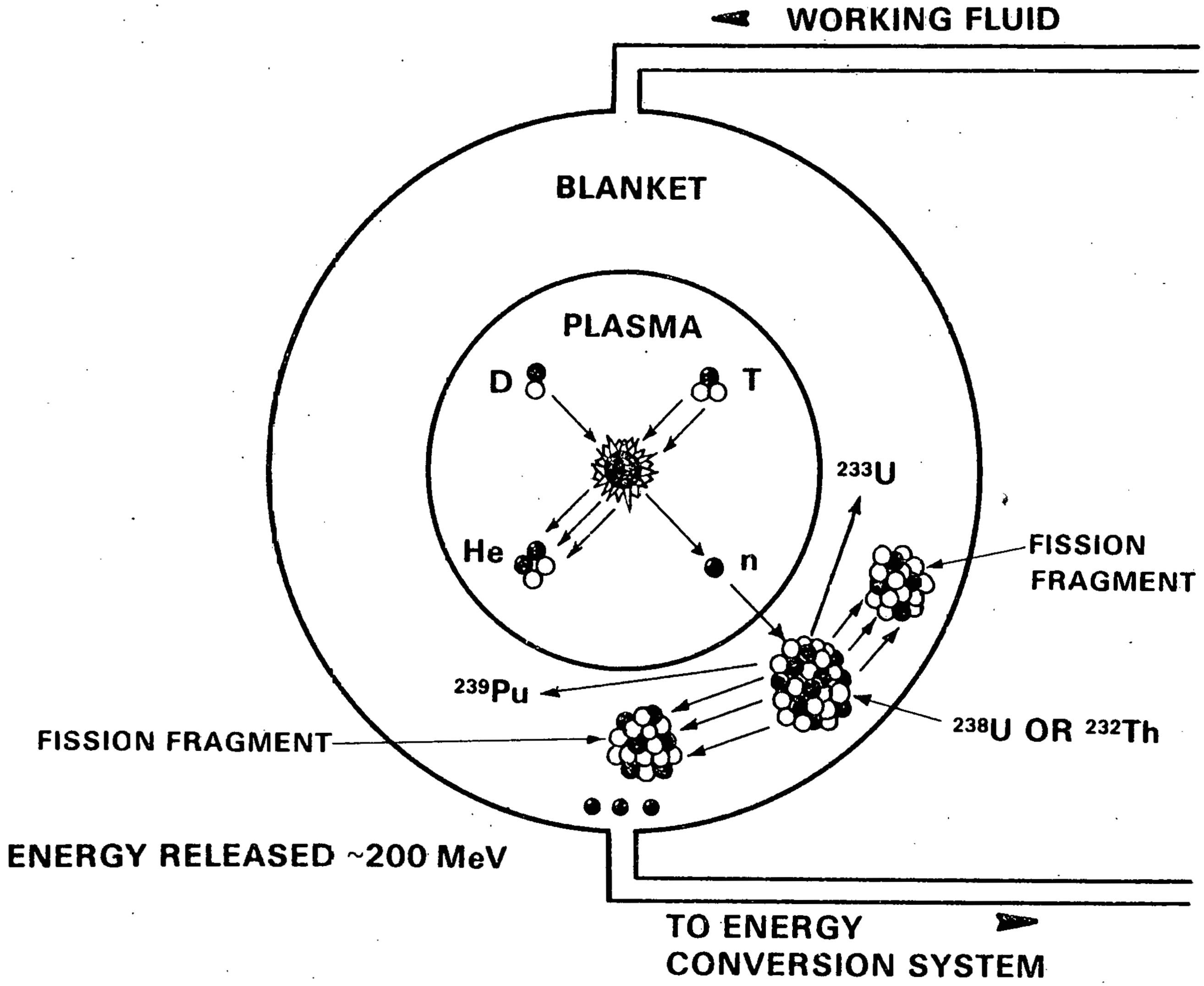

FIGURE 2

FIGURE 2. Fusion-Fission Process

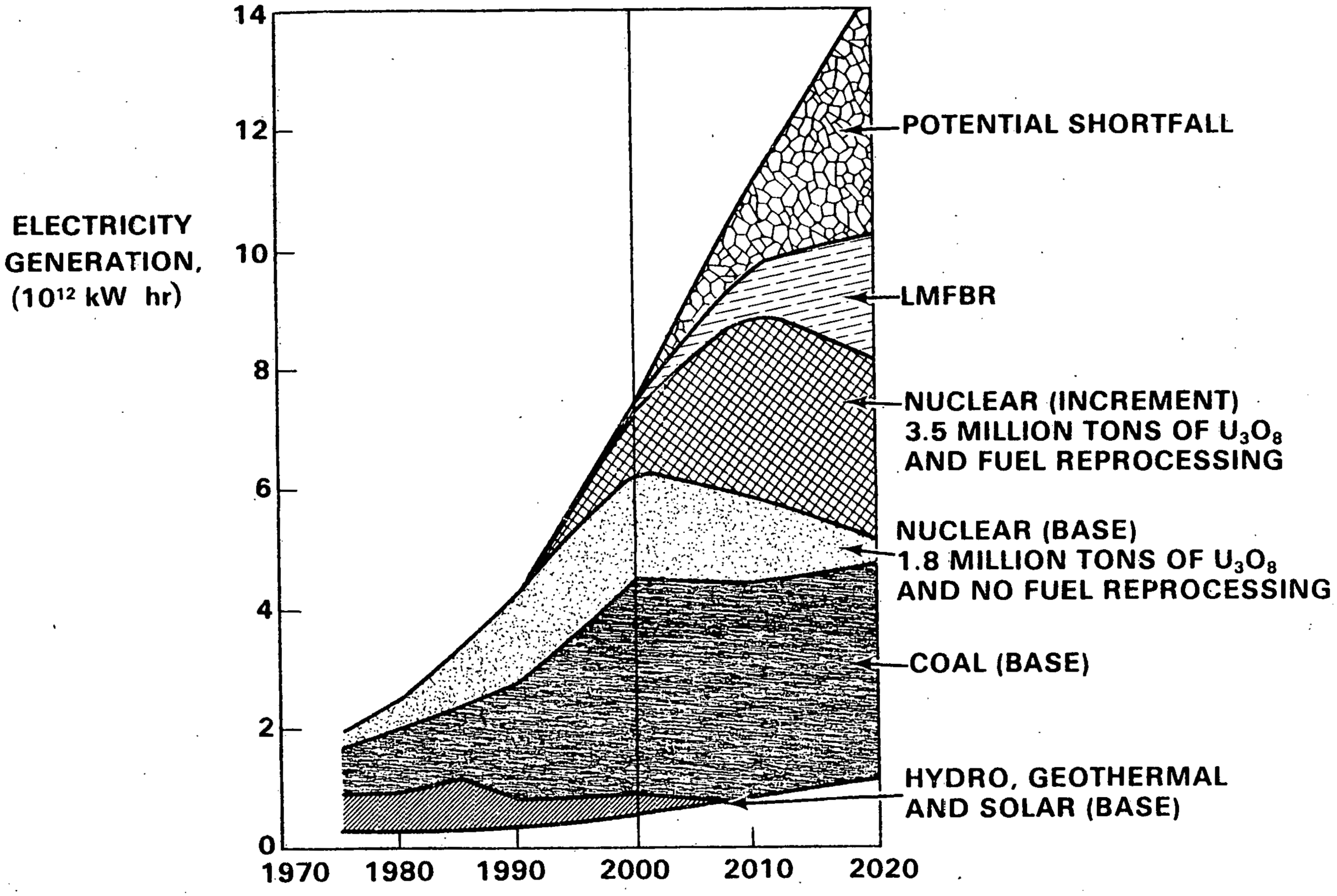

FIGURE 3. Projected Electricity Generation Mix, 1975 to 2020 (Reference 1)

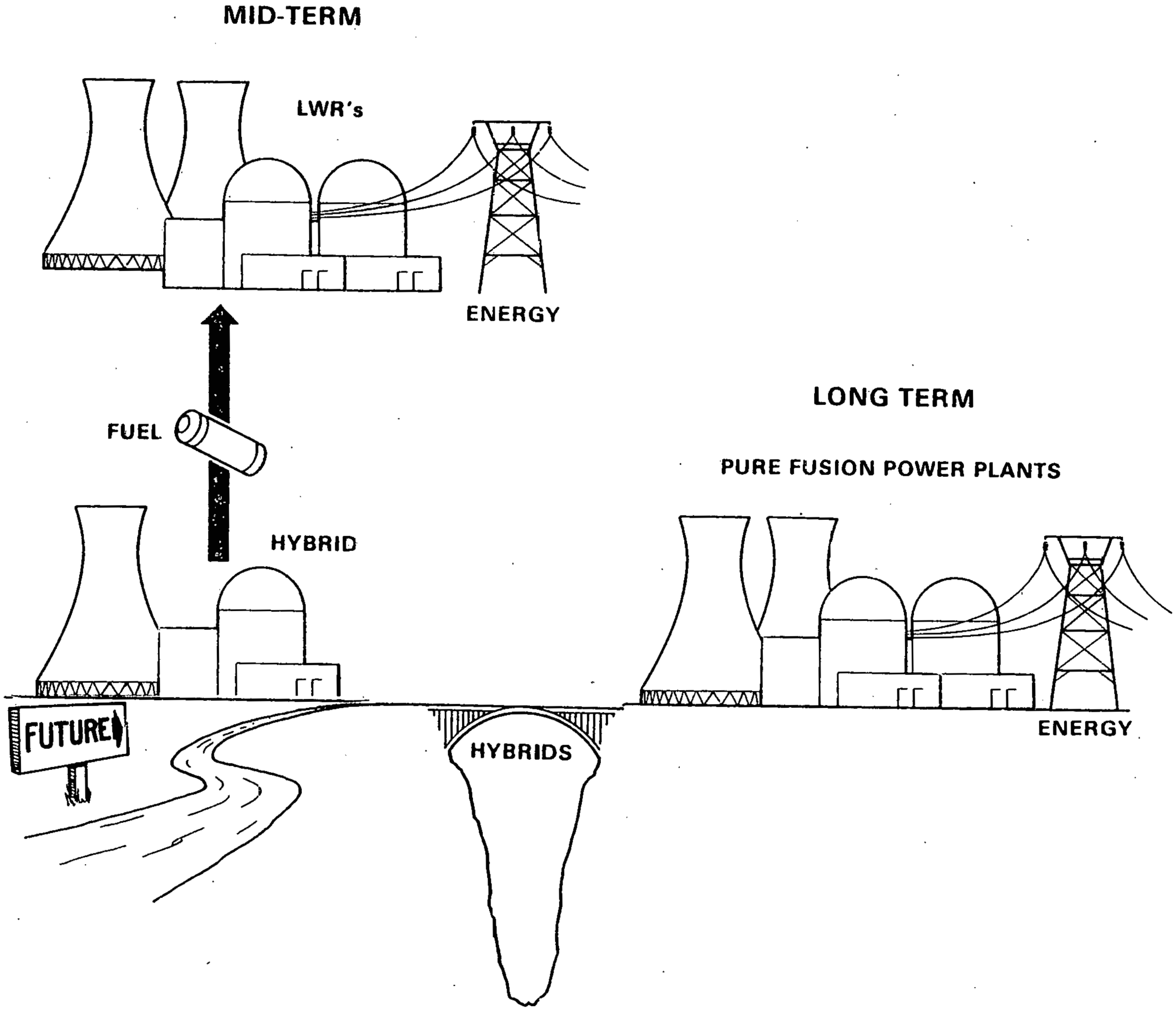

FIGURE 4. Where the Hybrid Concept Seems to Fit in

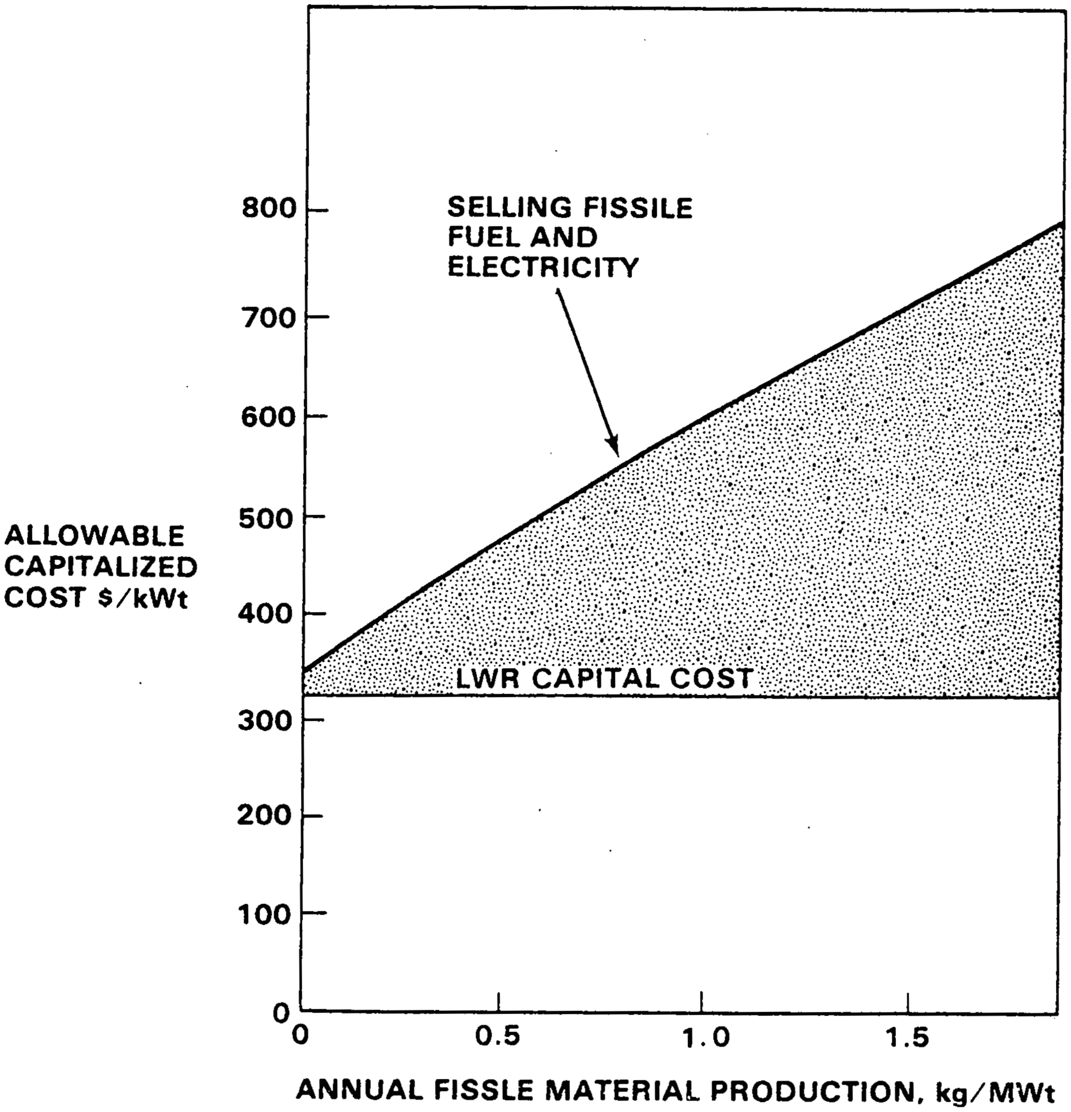

FIGURE 5. Market Penetration for Hybrids Producing Only Fissile Fuel for Sale

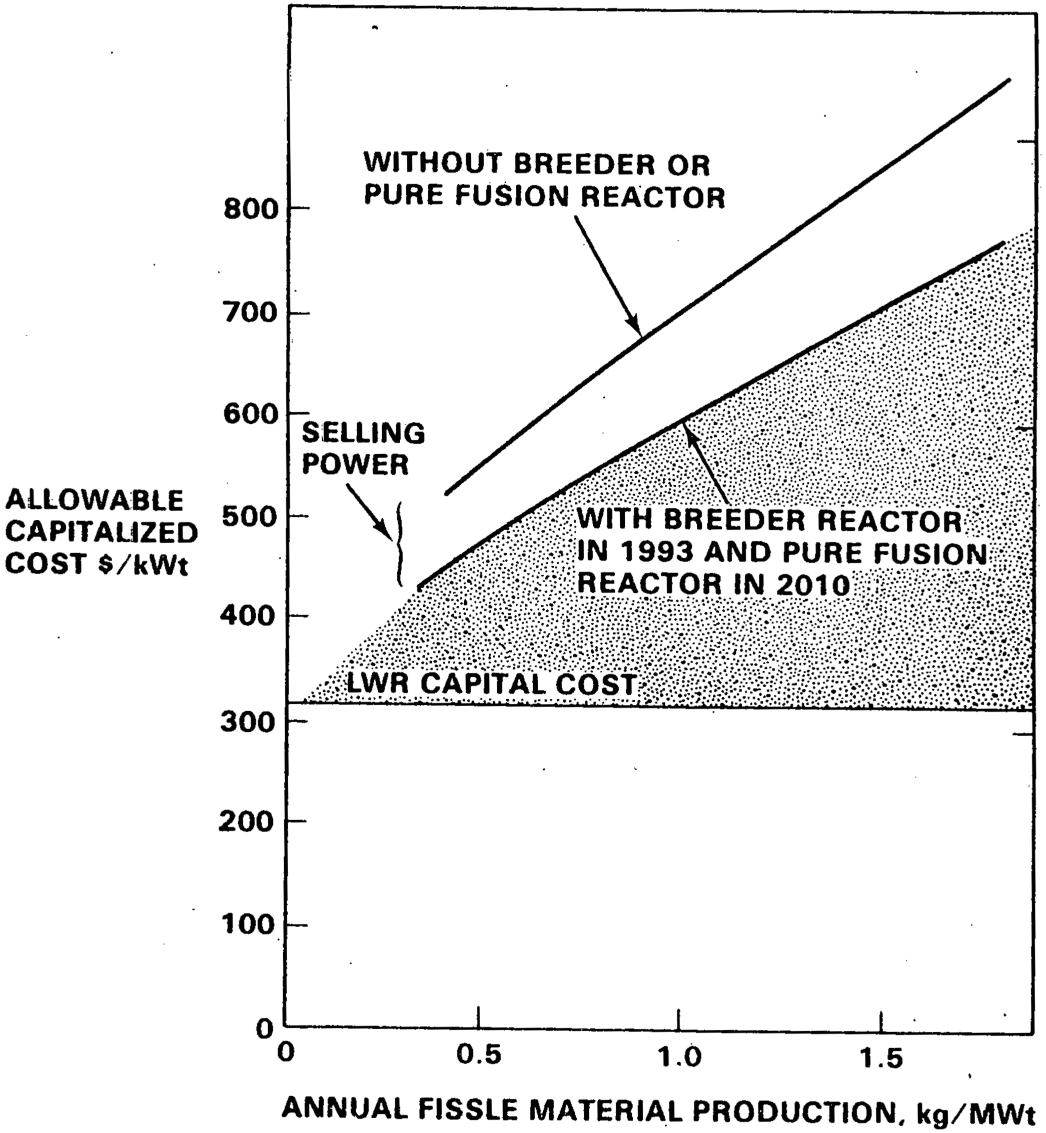

FIGURE 6. Market Penetration for Hybrids Producing Both Fissile Fuel and Electricity for Sale

HYBRID CONCEPTS

HYBRID MARKET PENETRATION

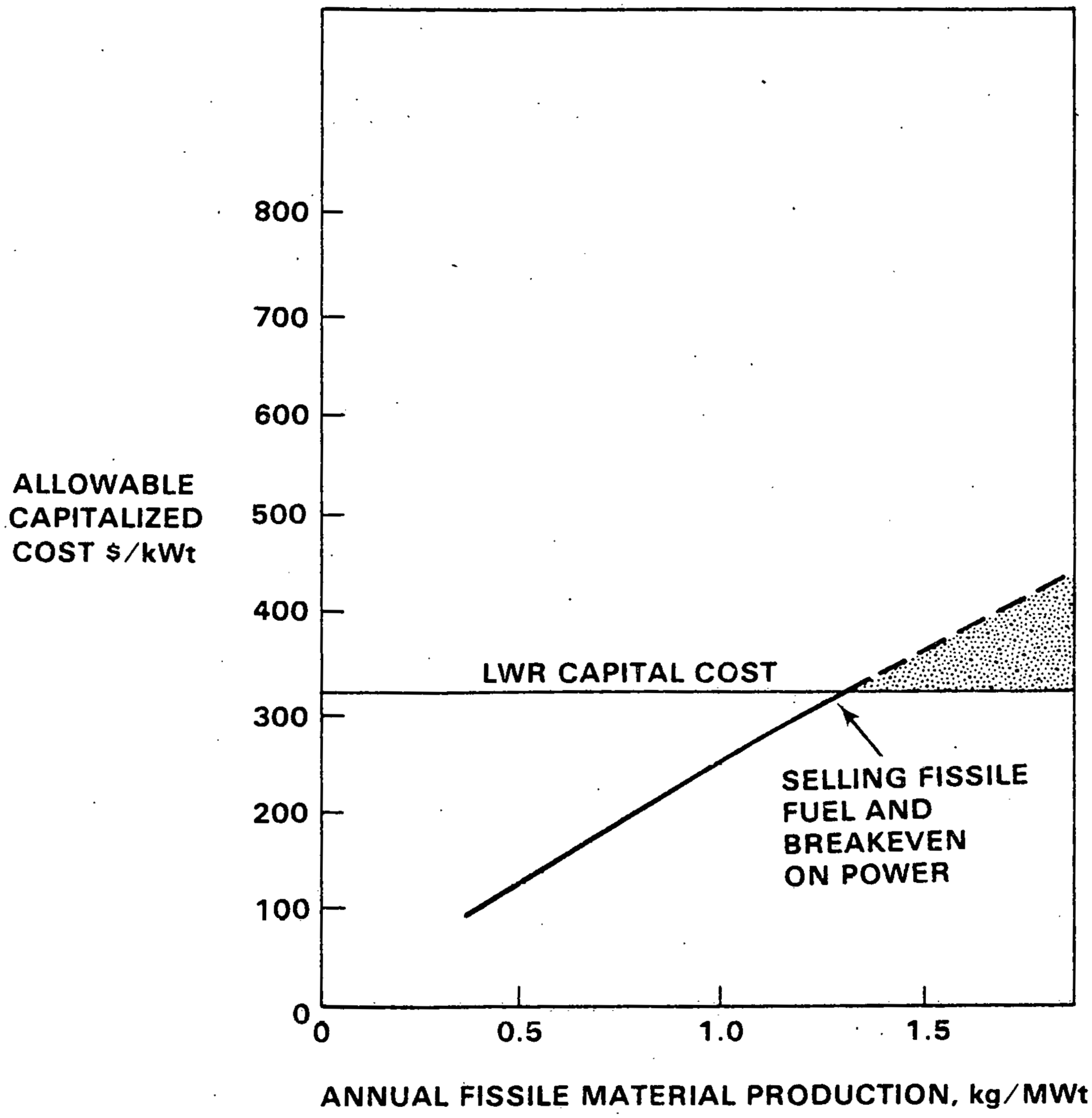

FIGURE 7. Effect of Competition on Hybrid Market Entry

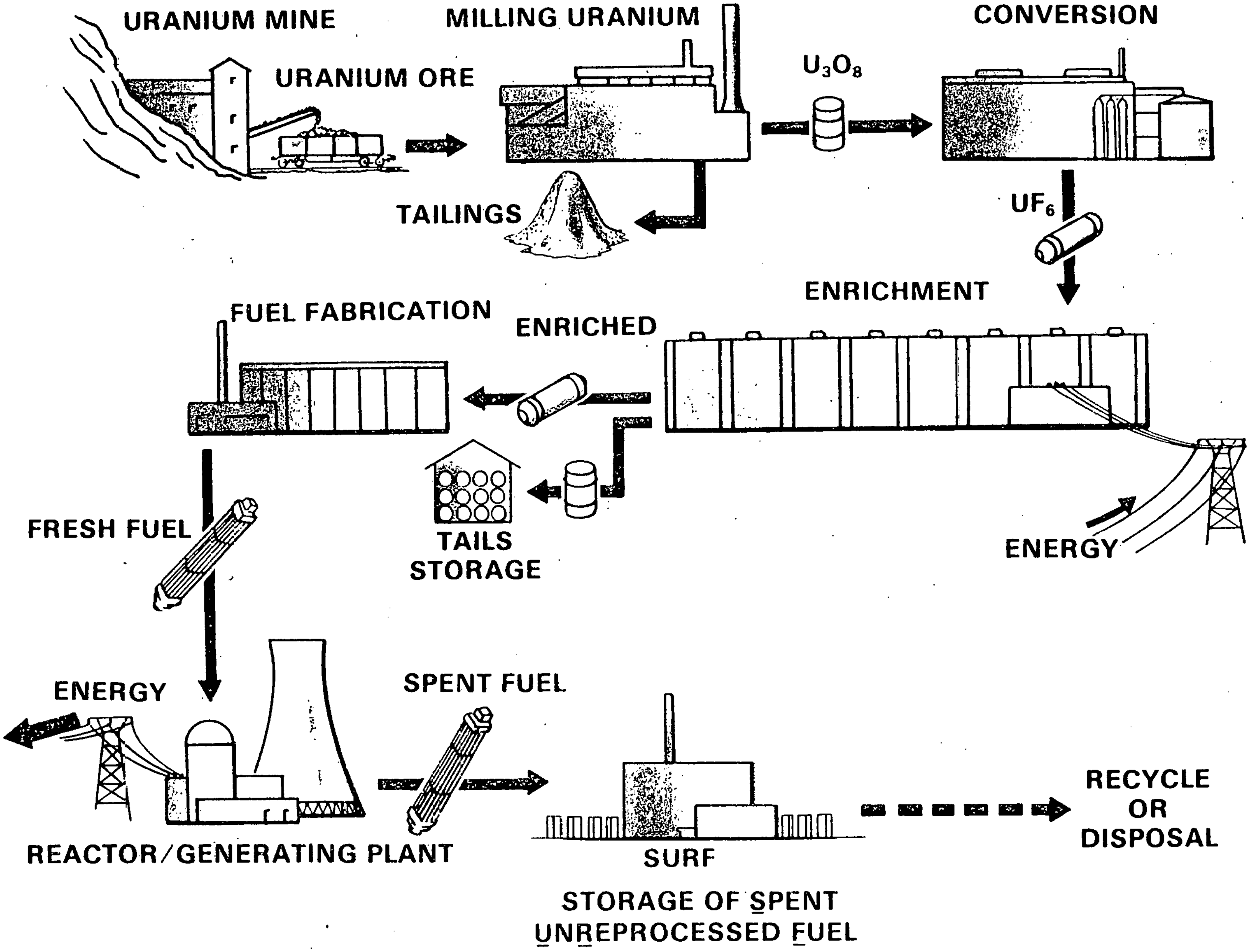

FIGURE 8. Nuclear Fuel Cycle

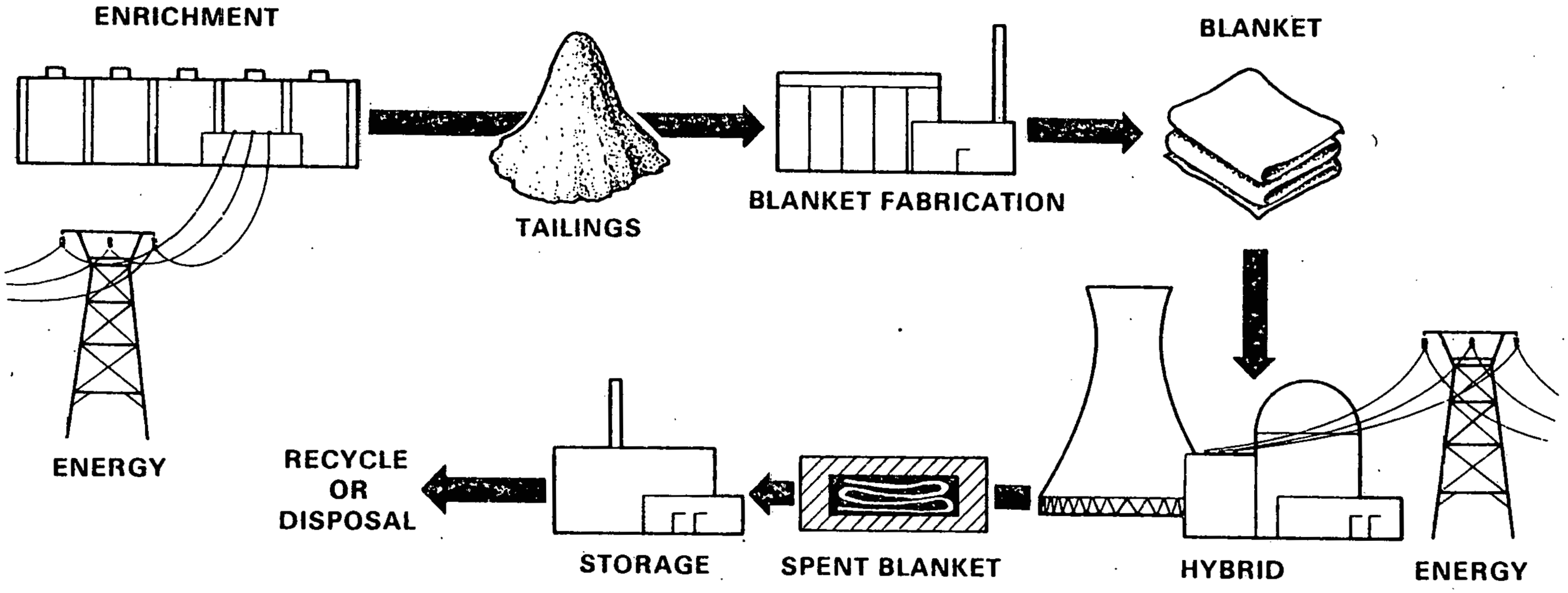

FIGURE 9. Throwaway Blanket Concept for No Reprocessing Scenario

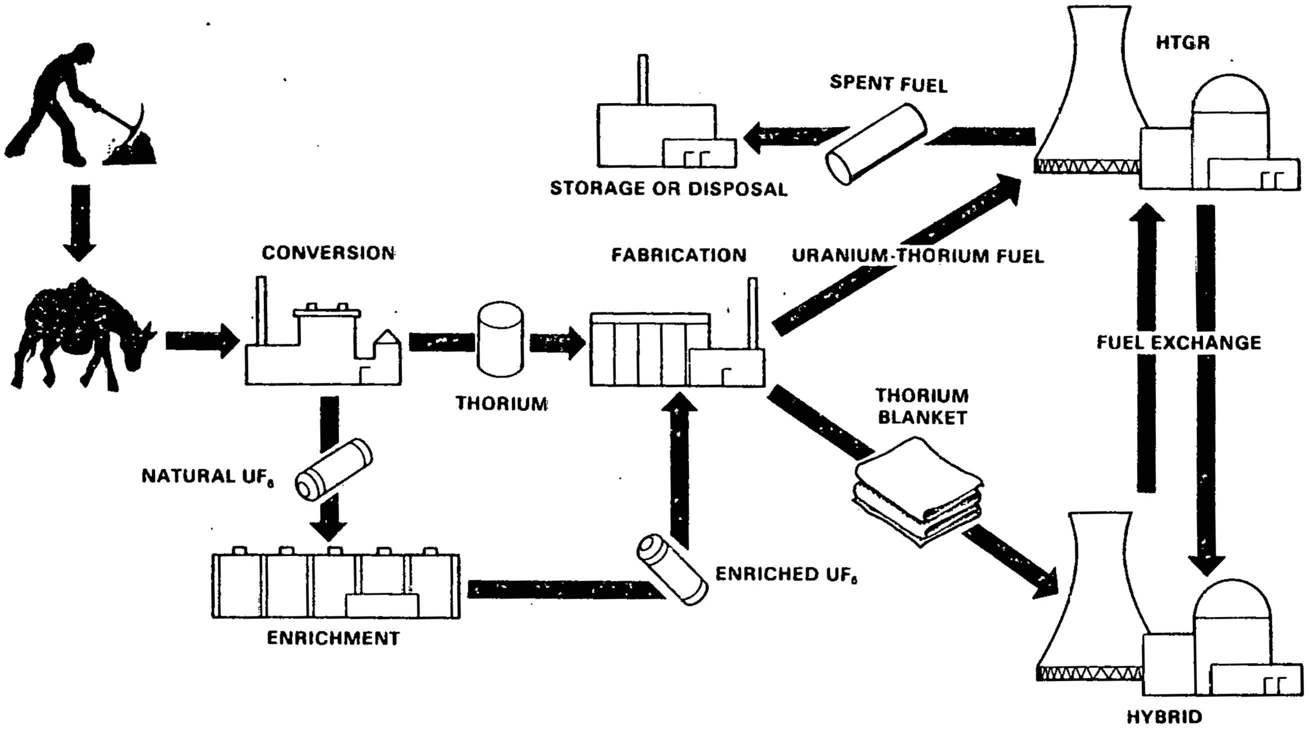

FIGURE 10. Refresh Cycle Hybrid Concept for No Reprocessing Scenario

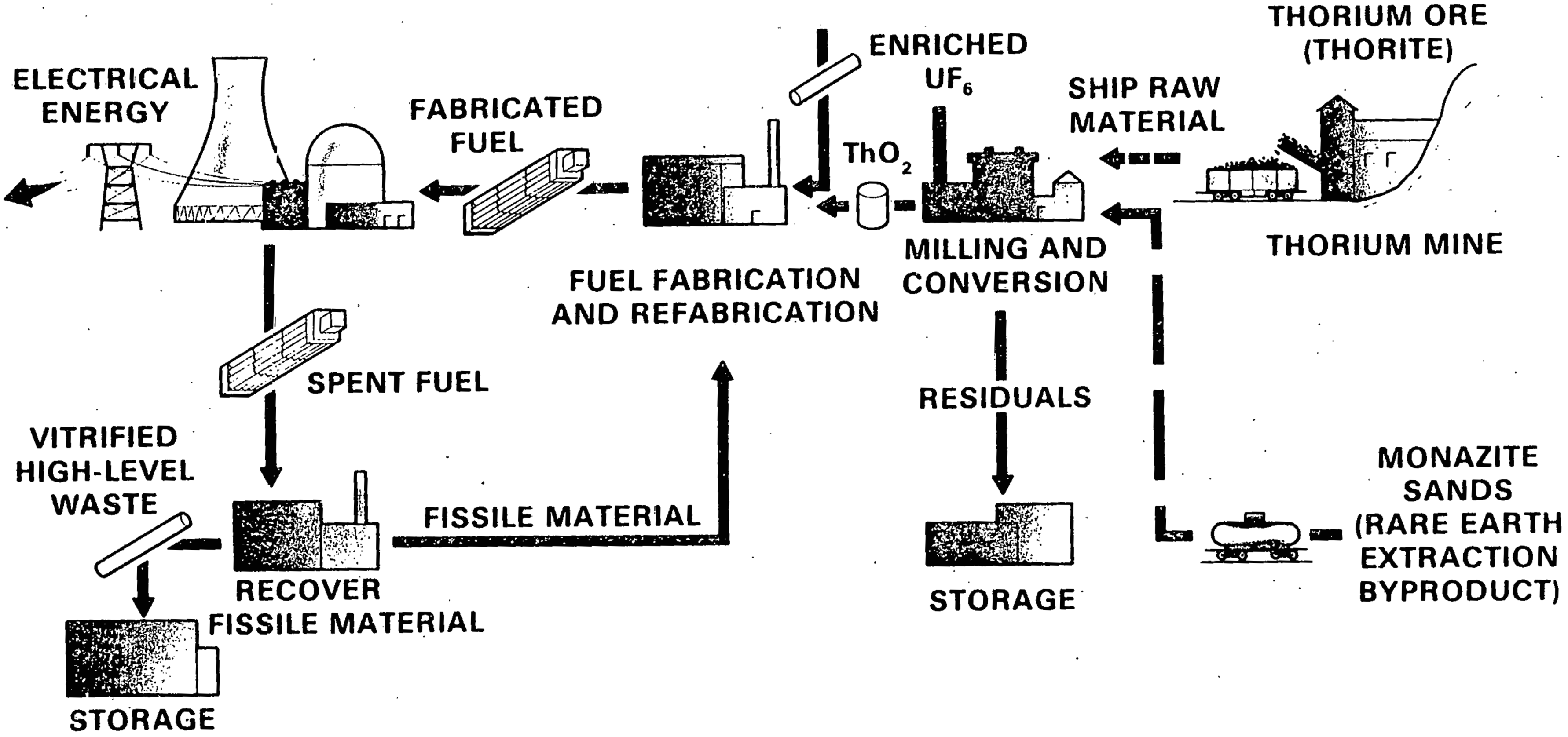

FIGURE 11. Thorium LWR Fuel Cycle

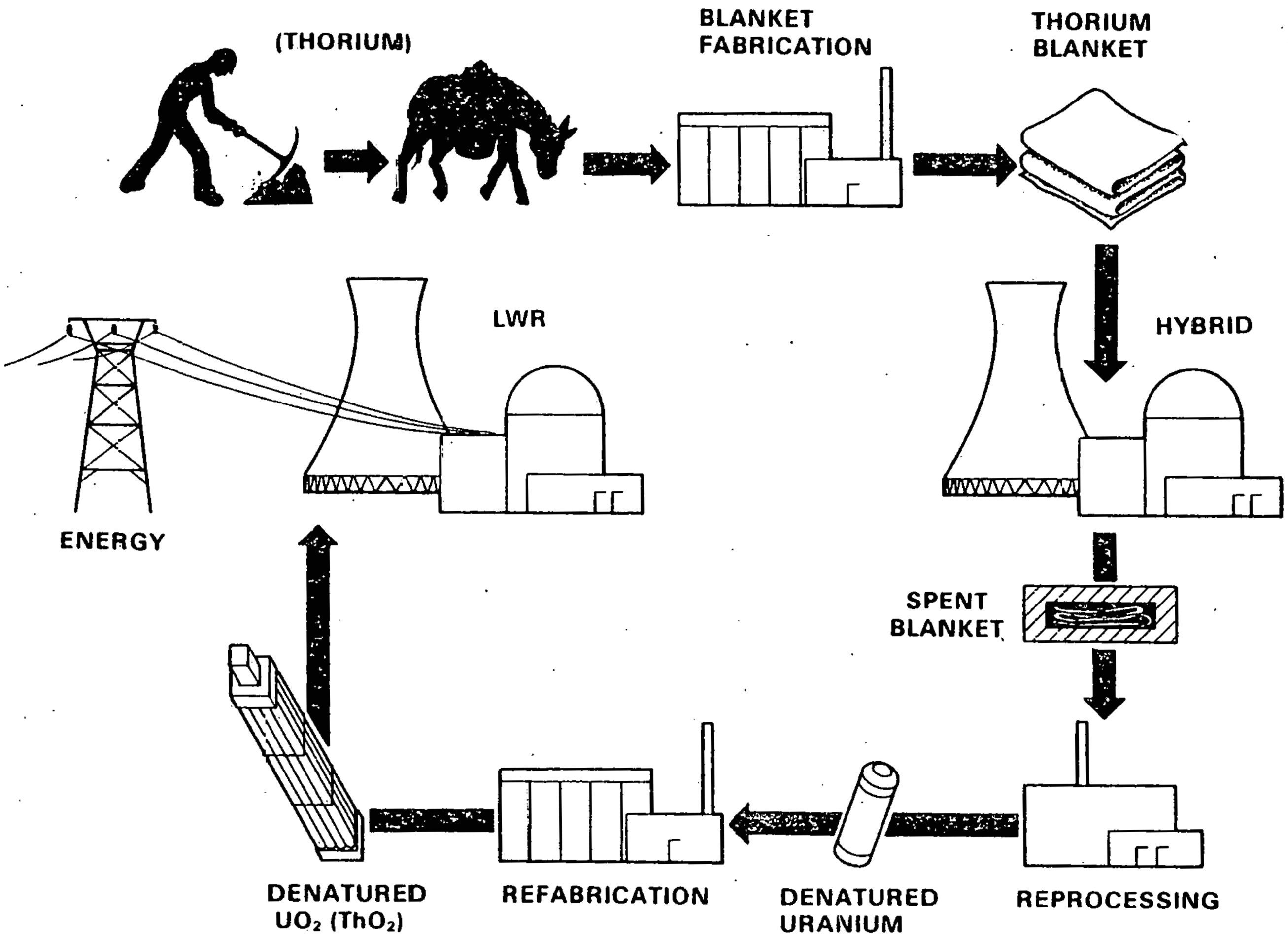

FIGURE 12. Hybrid Concepts for Restricted Reprocessing Scenario

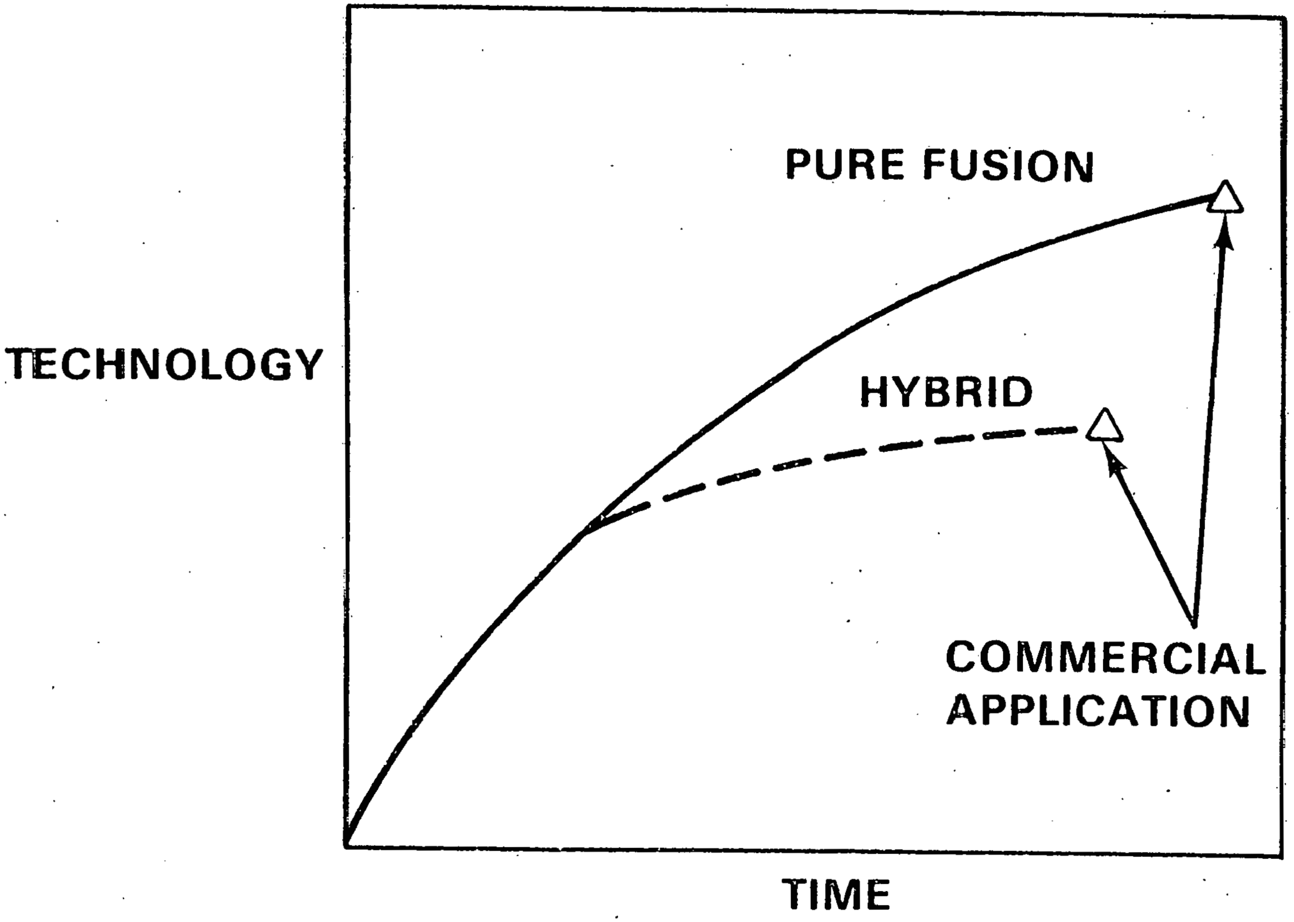

FIGURE 13. Hypothetical Fusion Technology Pathway

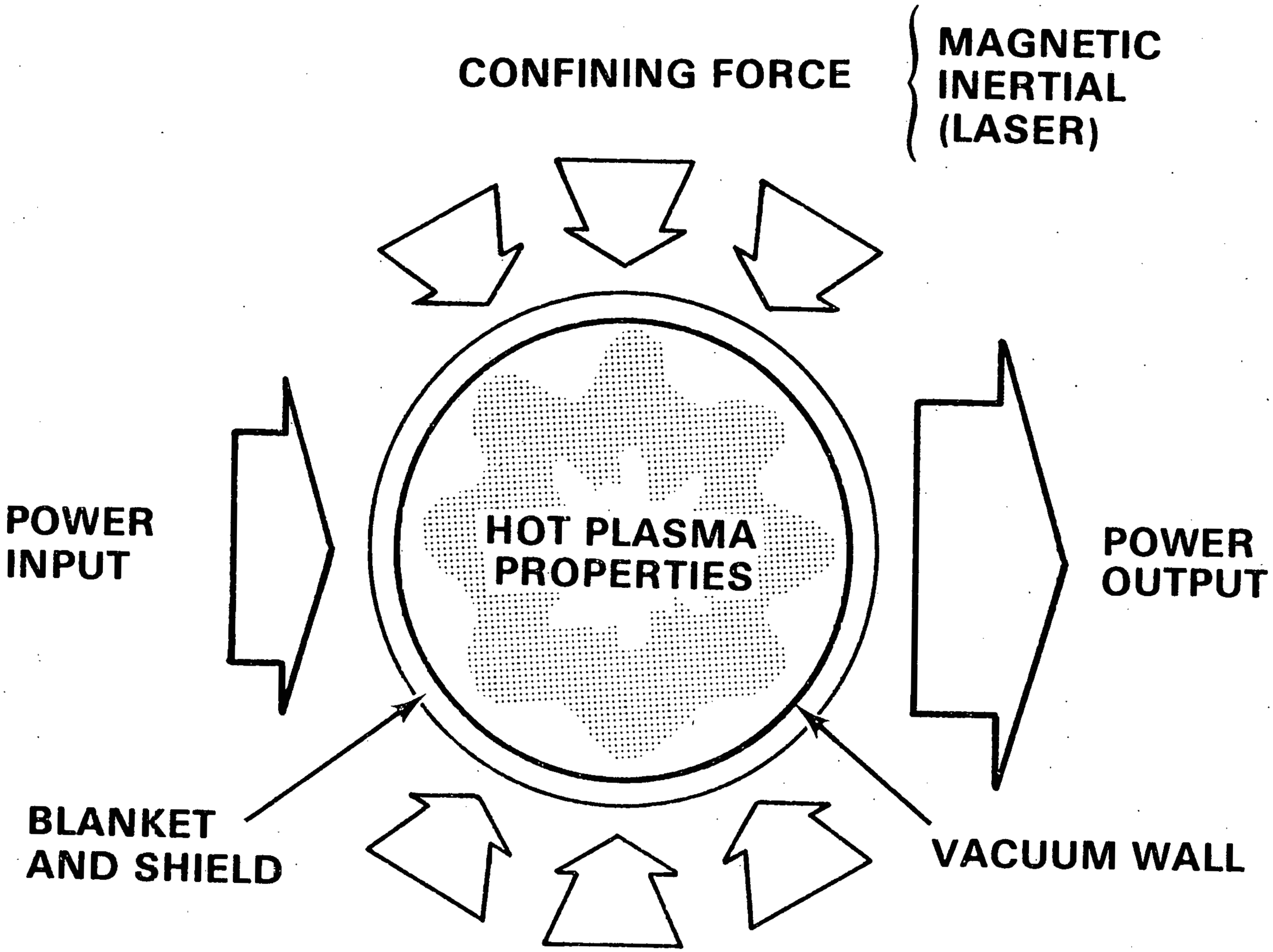

FIGURE 14. Technology Requirements

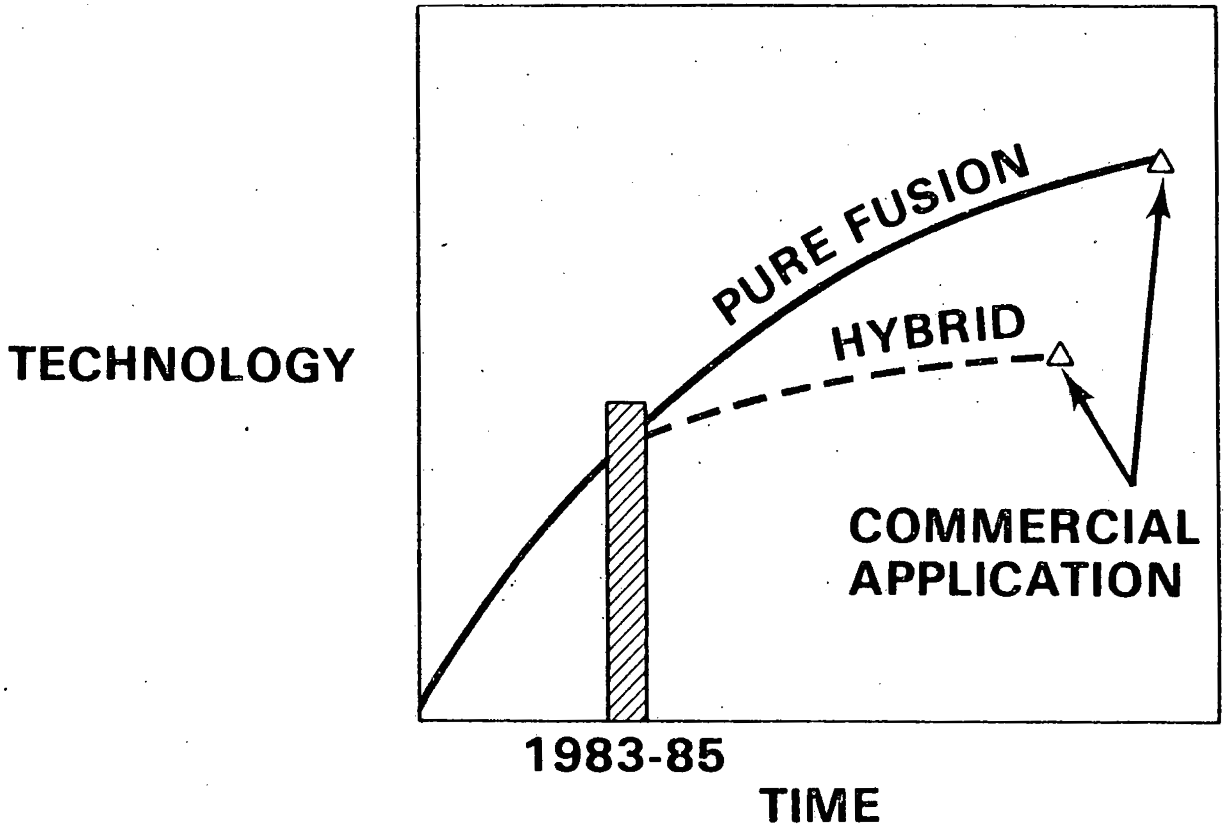

FIGURE 15. Hypothetical Fusion Technology Pathway

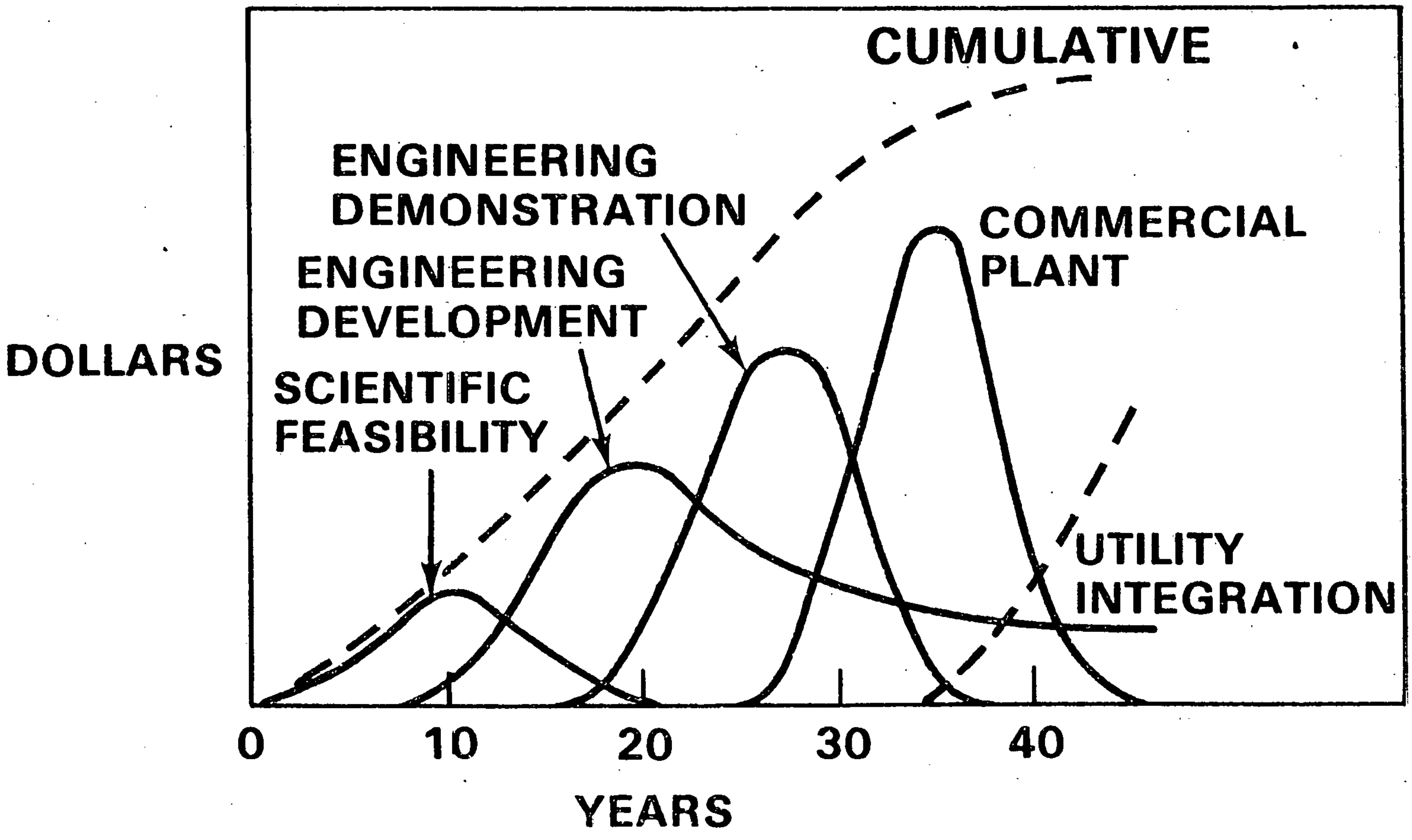

FIGURE 16. Commercializing a New Technology

PNL-SA-6492

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