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EXECUTIVE SUMMARY

1978 SOURCE BOOK

FOR

FUSION-FISSION HYBRID SYSTEMS

By

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FOREWORD

The interest in the fusion-fission hybrid (FFH) concept has increased substantially in the past several years. The underlying incentives for this have been provided by the recent advancements in fusion plasma physics, as well as the potential application of FFH reactors as suppliers of fissile fuel to offset shortages of fissile fuel otherwise expected to occur at the beginning of the next century.

It has long been recognized that the FFH, if technically feasible, could be the most prolific net fissile fuel producer known to man. As such, it would anchor the cost of enrichment services by providing an alternative to gaseous and centrifugal enrichment facilities. Additionally, it would not be tied to a depleting ^{235}U supply as the current enrichment technologies but could use depleted fertile material as a feedstock. Also, it could anchor the cost of yellowcake produced from ores with a continuously declining average ore grade.

These facts, combined with the perception that the fusion's scientific feasibility may be within reach, have prompted the U.S. Department of Energy as well as the Electric Power Research Institute to take decisive steps toward establishing a comprehensive assessment program for the FFH concept.

As part of the initial efforts, this study summarizes the promise and timing of the FFH concept and culminates in a generic RD&D timetable. This document emphasizes the meaningfulness of the concept to tomorrow's energy needs and energy production systems rather than strict analysis of technical feasibility.

The basic input for this assessment was derived from a general literature review and from direct and telephone conversations with many people who have been deeply involved, for many years, in theoretical and experimental

research, technical and economic assessment, and conceptual design of various fusion concepts, fusion-fission concepts and related technologies.

The study reports the results of a nationwide survey of views of such experts, on the subject of the timetable for the development of the FFH toward commercialization. The proposed RD&D timetables received as of printing time are summarized on page 1-34. Not surprisingly, considerable discrepancies exist among the various estimates because:

- (a) they were formulated for different FFH concepts for which the current levels of plasma physics advancement and RD&D funding vary markedly from one to another; and,
- (b) the timetables proposed reflect the differences of views among the persons involved with regard to: confidence level in plasma physics advancements; project completion time intervals; and, development program strategy.

Based on this information as well as on the UE&C experience as an Architect-Engineer which has designed, licensed, and constructed many nuclear and fossil power plants to date, the authors proposed a generic RD&D timetable for the FFH concept as a whole. This is given on page 1-34 and illustrated graphically in Figure 1.6.

While differences of opinions may exist on the specific milestones indicated, it is felt that the suggestion of the 2005 to 2010 time frame for the startup date of the first commercial FFH installation is an accurate representation of the general consensus of views within the fusion community.

John H. Crowley
Project Manager

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1978 SOURCE BOOK
FOR
FUSION-FISSION HYBRID SYSTEMS

SECTION 1.0

EXECUTIVE SUMMARY

1.1 INTRODUCTION

The 1978 Source Book for Fusion-Fission Hybrid Systems was prepared by United Engineers & Constructors Inc. for the U.S. Department of Energy and the Electric Power Research Institute. It reviews the current status of fusion-fission hybrid reactors, and presents the prevailing views of members of the fusion community on the RD&D timetable required for the development and commercialization of fusion-fission hybrids. The results presented are based on a review of related references as well as interviews with recognized experts in the field. Contributors from the academic and industrial communities are listed on page 1-36.

1.2 SIGNIFICANCE OF NUCLEAR ENERGY TO MAN'S ENERGY NEED

The earth has been endowed with solar derived fuels on a timetable embracing millions of years. Chemical energy can be provided by solar derived fuels consisting of wood, coal, gas and oil which have been man's source of energy for thousands of years. However, significant depletion of these solar derived fuels, particularly petroleum, is predicted to be just a few decades away which may be debatable but its eventual occurrence is not. By contrast, relatively recently discovered nuclear energy produced by the fusion of two light nuclei or fissioning of a heavy nucleus offers a virtually inexhaustible source of energy.

If the energy released by the chemical reaction of carbon and oxygen to form CO_2 is expressed as unity, then the energy released by fusion of a tritium atom and a deuterium atom is 50 million; the energy released in nuclear fission by splitting one atom of uranium metal is 588 million. Clearly, energy

production as measured by the mass of material required for a given energy release, is far greater for chemical reactions than nuclear. A similar comparison of waste products produced for a given energy release highlights another aspect of nuclear energy efficiency.

The fusion process of the sun is an extreme example of efficiency of chemical versus nuclear energy. If the total energy of the sun were produced by coal, it would consume the entire United States coal reserves in 3.8×10^{-5} seconds or about 0.4 of a microsecond. Moreover, in 24 days an ash sludge residue equal to the size of the earth would be generated. Although this is an extreme analogy, the intent is to relate the efficiency of energy production and waste quantities accumulated for nuclear reactions compared to chemical reactions. Increased world emphasis on environmental effects requires better understanding of the significance of these relationships and their overall impact.

Energy generated from nuclear reactions was discovered and demonstrated several decades ago. Knowledge of nuclear phenomena and the engineering problems associated with extracting useful energy led to the early belief in the following scenario for deployment of nuclear technology. Initially, fission converter devices such as light water reactors (BWR and PWR) would be deployed. Next, the advanced converters such as CANDU and HTGR reactors would appear. Finally, as uranium reserves become depleted, breeder reactors, fusion electric and solar energy as the technology evolved would begin to contribute significant amounts of energy in the early-to-mid decades of the twenty-first century.

Events have not proceeded according to this scenario as initially envisioned. The advanced converter program in the United States was virtually abandoned, except for a minor HTGR program. The Canadian CANDU and German gas cooled pebble-bed concepts are proceeding. Deferral of the commercial breeder program in the United States will in all probabilities prolong significant energy contributions until well into the next century. To make maximum use of the terrestrial uranium resources, the only source of fissile fuel in nature, it has generally been presumed in the past that fission breeder reactors capable of producing more fuel than they consume would become necessary ingredient for a viable nuclear energy economy. The engineering and scientific feasibility of this approach has been adequately demonstrated in Great Britain, France, USSR and the United States. Consequently, the French Phenix and Super Phenix projects are proceeding on a planned commercialization program. For the near term, however, availability of nuclear energy will be limited to Light Water Reactor (LWR) technology.

1.3 NEED AND AVAILABILITY OF NUCLEAR FUEL

A utility decision made today to build a LWR plant based on current project schedules has to consider that the plant would not come on line until the early 1990's. Furthermore, fuel supply would have to anticipate nuclear fuel market conditions during the 1990 to 2020 time frame. Despite the adverse political pressures and initial fuel inventory uncertainties of commercial breeders, substantial LWR capacity will continue to be committed beyond existing commitments through the years immediately ahead, because of increasing environmental pressures on use of coal. This large commitment to LWRs increases the demand for enriched uranium and results in serious

questions about the availability and cost of uranium concentrate and enrichment services over the lifetime of all committed reactors. This concern was stated in a recent 1978 OECD* report entitled, "Nuclear Fuel Cycle Requirements" as follows:

"An analysis of alternative reactor strategies makes it clear that continued reliance on thermal converters in the period after 2000 will result in the rapid depletion of known uranium resources and will relegate nuclear power to a minor role in satisfying the world energy needs. The use of advanced near-breeders (including those which utilize thorium) can do much to reduce the total requirement for uranium, but those requirements will still result in the eventual depletion of known reserves. On the other hand, breeder reactors if demonstrated to be economically feasible, would provide a virtually inexhaustible source of energy supply within foreseeable extensions of known uranium resources."

Most projections of uranium supply and demand for the early decades in the twenty-first century show uranium being supplied from "speculative" sources further increasing the uncertainties of price and availability. Similarly, projections of supply and demand for enrichment services indicate that a significant increase in world capacity is required. To meet these requirements, uncertainties associated with the large capital requirements and unformulated international agreements on antiproliferation policies must be considered. Figures 1.1 and 1.2 showing uranium and enrichment forecasts indicate a significant potential shortfall for the early decades of the twenty-first century.

Reasonable assurance of a viable uranium and enrichment service supply is a significant factor in decision for utility commitment to a nuclear power plant.

*The Organization for Economic Cooperation and Development (OECD) was set up under a Convention signed in Paris on December 14, 1960 by 24 countries including the United States.

World cumulative uranium requirements may exceed resources early in the next century. Projections are based on OECD/IAEA estimates of a low growth of nuclear fission power and resource costs up to \$130 per kilogram uranium.

Figure 1.1 Cumulative World Uranium Demand versus Resources

Annual enrichment requirements of the world may exceed capacity before the next century. Projections are based on OECD/IAEA estimates.

Figure 1.2 Annual Enrichment Demands Versus Capacity

In addition to the electrical sector's demand for nuclear fuel, reasonable evidence exists to suggest at the beginning of the twenty-first century an ever-increasing demand for nuclear power to support the industrial and synfuels (synthetic fuels) sector of the world economy. At the present time, both sectors rely on oil, natural gas or coal as their thermal energy sources. Most surveys of world petroleum resources and reserves anticipate a gradual decline in world oil production at the beginning of the twenty-first century. This occurrence may result in either an increase in the electrical demand as electricity is substituted (unfortunately, at lower efficiency) for petroleum or the appearance of a coal derived synfuels industry.

The inefficiencies of the industrial and synfuel processes and the current tendency to use coal as a fuel and feedstock will result in an exponential increase in the consumption of coal and an attendant exponential increase in the environmental impacts associated with that energy source. Should environmental concern on air pollution, solid waste disposal, contaminated runoff, and atmospheric CO₂ accumulation require a reduction in the utilization of fuel coal, nuclear energy in the form of high temperature reactors may be required to pick up the shortfall. The net impact could be that the demand for natural fissile uranium and enrichment services will exceed the current demand projections.

Most inexhaustible energy sources cannot economically provide the large amounts of high temperature energy demanded by the industrial and synfuels processes. Since failure to deal with this environmental/energy dilemma will have a profound effect on the world economy, nuclear energy may have to fill the gap. It could become necessary to utilize the potential energy available

from the accumulated ^{238}U tails, natural uranium and thorium ores. Therefore, the need will be for a fissile fuel factory to provide fuel for nuclear process heat in addition to nuclear electric power generation.

1.4 POTENTIAL CONTRIBUTION OF THE FUSION-FISSION CONCEPT

A fusion-fission hybrid device consists of a subcritical fast fission interface blanket and one of a number of specially designed after-blankets surrounding a fusion reactor. Depending on the design of the after-blanket, the hybrid can produce fissile fuel and/or electricity. Figure 1.3 schematically presents a hybrid device compared to a fusion electric device. The hybrid promises a significant contribution to the solution of the world energy problem and provides another incentive for early development of fusion technology. The expected performance of the hybrid and technological targets associated thereto are potentially closer to our current technology than fusion electric. This may result in an earlier commercial availability of the hybrid as compared to that of the fusion electric device. Thus, the hybrid has the potential to assure a supply of fissile fuel for existing and newly deployed LWRs and advanced converters in the early decades of the twenty-first century.

1.4.1 Description of Fusion-Fission Physics

The specific fusion reaction, envisioned as a near-term possibility, releases significant energy when the nuclei of deuterium and tritium are fused to produce a helium atom and a neutron. The mass difference between the products formed and the reactants produces about 17.6 MeV of energy for each fusion event, the distribution being 3.5 for the He ion (alpha particle) and 14.1 MEV for the neutron. The fusion electric reactor depends on the conversion of this energy to maintain the temperature of its plasma and thus sustain the reaction. The neutrons may be used to convert lithium into additional tritium atoms, to resupply the fuel for the fusion reaction.

Figure 1.3 General Schematic of Fusion Electric and Fusion-Fission Hybrid

The hybrid uses the 14 MeV neutrons to drive an otherwise subcritical fertile blanket producing fission and other reactions. The 14 MeV fusion neutrons interact with the uranium, ^{238}U , and/or thorium, ^{232}Th , in the fertile blanket by fast fission, (n,2n) and (n,3n) reactions to multiply the energy by factors of ten or more and generate more than four neutrons per event for breeding of fissile and fusile materials.

1.4.2 Prolific Fuel Production

Based on these performance characteristics, one hybrid reactor with reprocessing could provide fissile fuel for five to ten LWRs utilizing natural, depleted or recycled fertile material as a feedstock. Early development of hybrids supporting a well developed converter technology in the world's electrical, industrial and synfuels sectors, could permit the conservation of irreplaceable petroleum and coal fuels and provide insurance against unforeseen and potentially catastrophic-forced reductions of fossil fuel utilization because of environmental concerns.

1.4.3 Proliferation Resistant "Refresh" Fuel Cycle

The opportunity to develop and support proliferation-resistant refresh or denatured cycles is enhanced by deployment of the hybrid. This is attributable to the fact that the refresh cycle revitalizes spent fuel by means of recycling it through the hybrid, as opposed to extracting fissile fuel from the spent fuel by present methods of reprocessing. Also, the denatured cycle allows use of fertile-to-fissile fuel mixtures not conducive to weapons diversion.

1.4.4 Relaxed Engineering Requirements

The hybrid's fission-blanket neutron and energy multiplication characteristics result in a relaxation of plasma physics requirements for the fusion driver

of a fusion-fission hybrid producing electricity as compared to a fusion electric-generating device. In addition, if the hybrid is dedicated to fissile fuel production and does not supply electricity to the grid, the engineering requirements for the entire plant may be considerably relaxed as compared to a fusion electric device. This follows, because the plant reliability and availability requirements for the production of fissile fuel production should not be as stringent as those for electricity generation. Therefore, the engineering and technological requirements of the hybrid may be closer to our current technology than those for fusion electric generating plants.

1.4.5 Improved Breakeven Energy Requirements

For the fusion electric device, the ratio of the energy produced to the energy needed to initiate and sustain the reaction (sometimes designated Q) must equal one for the breakeven condition. Such a machine is not a net power producer. For net power out of a fusion electric reactor, a Q greater than 5 is needed. Currently planned fusion experiments are expected to reach the breakeven point, $Q = 1$, sometime in the early 1980s. Figure 1.4 indicates fusion research progress points towards attaining plasma conditions suitable for fusion-fission applications ($Q = 1$) within the next five years. The prospects for the fusion reactor as a net producer of power appear promising but are not anticipated until the end of this century. Commercialization will occur in the early decades of the next century resulting in significant contributions from fusion electric to the world's electrical energy supply in the 2030 to 2040 timeframe. The hybrid, in contrast to the fusion electric reactor, does not require as high a Q ratio either for producing fissile (and fusile) fuels or for energy production. The Q values estimated for satisfactory operation of a hybrid are in the range from two to five. This is a significant reduction in the physics constraints of the fusion

Fusion research progress points towards attaining plasma conditions suitable for fusion-fission applications ($Q \approx 1$) within the next five years.

Figure 1.4 Progress in Fusion Research

electric device. Summaries of physics parameters appear in Table 1-1. Thus, fusion technology with respect to plasma conditions appears achievable in the near term for hybrid applications. All of these factors permit practical development of the hybrid to proceed on a potentially shorter timetable than fusion electric.

1.4.6 Rapid Deployment

In addition to the potentially longer development schedule, fusion electric generating plants like any advanced power producers, probably would take 30 to 40 years after a commercial demonstration before they could be deployed in sufficient quantities to provide a significant portion of the electrical demand. The coupling of the hybrid's fissile fuel production to the existing LWR technology should result in a more significant as well as an earlier energy contribution. Finally, the application of less demanding fusion physics conditions in hybrids, encourages earlier attention to the engineering, construction and operational aspects of fusion reactors, than might occur if attention were confined only to fusion electric. This more balanced approach to the total requirements for practical fusion power could help when engineering is begun for the first commercial fusion electric generating plants. Numerous relevant systems and subsystems of the hybrid device would be applicable to the fusion electric device. The hybrid would not only meet the LWR or other fission reactors fuel supply needs in the early part of the twenty-first century but it could strengthen the economic and technical support for the development programs required to achieve fusion electric.

TABLE 1-1

COMPARISON OF THE STATE-OF-THE-ART TECHNOLOGY AND CHARACTERISTICS
OF FUSION ELECTRIC AND FUSION-FISSION HYBRID REACTORS

<u>Plasma Conditions</u>	<u>Symbol</u>	<u>Current Technology</u>	<u>Fusion-Fission Hybrid Characteristics</u>	<u>Fusion Electric Reactor Characteristics</u>
Plasma Density ₃ (particles/cm ³)	n	< 10 ¹³	> 3 x 10 ¹³	> 10 ¹⁴
Plasma Confinement Time (seconds)	τ	< 10 ⁻¹	~ 1	> 1
Lawson Criterion Density ₃ x Conf. Time (sec/cm ³)	nτ	< 10 ¹³	> 10 ¹³	> 10 ¹⁴
Plasma Temp. (keV)	T	< 6	5 - 10	≥ 10
[Plasma Pressure Magnetic Pressure]	β	< 0.01	> 0.02	0.03 - 0.05
<u>Input Variables</u>				
Magnetic Field Strength on Axis (Teslas)		≤ 3	≥ 4	≥ 5
Neutral Beam Energy (keV)		~ 100 (positive ion)	~ 100 (positive ion)	≥ 200 (negative ion)
Magnetic Power Input (Ohmic heating required in tokamaks)		≤ 5	~ 400	≥ 500 (1 to 10 seconds before startup)
Pulse Length (seconds)		< 1	≤ 10 ³	≥ 5 x 10 ³
<u>Output Variables</u>				
Power Output (MWt)				
Plasma		0	300	3,000
Blanket		0	3,200	500
Total		0	3,500	3,500
Neutron Wall Loading (MW/m ²)		low	< 2	2 - 5
[Fusion Power-Plasma Injection Power]	Q	0	2 - 5	> 5
Fiissile Fuel Pro- duction (kg/MW(t)-year)				
²³⁹ Pu		0	0.8 - 1.0	-
²³³ U		0	0.5 - 0.7	-
Power Unit Size			Demo	Comm.
MW(t)		0	3-50	~ 2,500 ~ 3,500
MW(e)		0		~ 800 ~ 1,200

1.4.7 Marketing Considerations

The hybrid's economics are uncertain at the present time, however, some effort has been devoted to "target" economics. Significant work is still needed to determine the actual construction as well as operation costs of the hybrid.

It is expected that the capital cost of the hybrid will exceed that of an LWR or LMFBR with identical thermal rating, but the final "production cost" (mills/kWh for the electric sector, or $\$/10^6$ Btu for synfuels and the industrial sector) as related to consumer cost, may well be competitive.

The hybrid, combined with reprocessing, is a prolific fuel producer providing fuel for five to ten LWRs. Figure 1.5 illustrates such a hybrid fuel producing facility. The final product cost of the energy produced by the hybrid's satellite converters is relatively insensitive to the cost of the hybrid itself. It is important to note that the hybrid's capital cost is determined by averaging over the total capital investment of the numerous satellite converters, such as the LWR.

It is not appropriate to consider the hybrid a replacement for the LMFBR, because of the uncertainty of cost information and because the LMFBR is not designed to be a fuel producer for advanced converters. Rather, the LMFBR is intended to be a replacement in the electrical sector only. The impact of the final end-use energy form on the value of a fuel and its conversion system cannot be overlooked. Considerable development and engineering is required for the hybrid, whereas the LMFBR concepts are well into the engineering and hardware stage.

A fusion-fission hybrid fissile fuel producing facility is estimated to provide makeup fuel requirements for 5 to 10 light water reactors.

Figure 1.5 Fuel Flow Diagram of Fusion-Fission Hybrid and Satellite Burner Reactors

The hybrid can be considered an anchor on the price of yellowcake produced from ores having continuously declining average ore grade. The hybrid can also be considered an inexhaustible fuel source for a nuclear technology that may serve the industrial and synfuels sectors as well as the electrical sector.

The R&D investment in developing and ultimately deploying the hybrid may be a more effective use of capital than the expansion of enrichment plants. Furthermore, unlike fuel enrichment plants, whose large capital investment is committed to a depleting ^{235}U resource, the capital investment in the hybrid is closely related to the deployment of a virtually inexhaustible fuel utilization cycle.

1.5 CURRENT VIEW OF THE FUSION-FISSION CONCEPT

Each of the fusion-fission concepts currently under study is described briefly below. In addition, the major parameters of each system is presented in Table 1-2. Table 1-2 also gives key parameters for LWRs for completeness. In addition, Table 1-3 summarizes the status of each concept by giving a tabulated assessment. The fusion-fission concepts reviewed are:

- o Tokamak Hybrid

One of the Tokamak hybrid designs developed by the Fusion Power Systems Department at Westinghouse is based on the beam-driven, Two-Component-Tokamak (TCT) principle and uses concepts similar to those of the Tokamak Fusion Test Reactor (TFTR) now being built at the Princeton Plasma Physics Laboratory. The fission blanket is UC and helium coolant is used.

- o Mirror Hybrid

A conceptual design of a commercial mirror hybrid reactor, optimized for ^{239}Pu production, was completed as a result of a joint effort by Lawrence Livermore Laboratory and General Atomic Company. Neutral-beam injection is used in a minimum-B magnetic geometry. The Yin-Yang magnets, blanket and primary heat transfer loops are all housed within a prestressed concrete reactor vessel (PCRV) of the HTGR-type. The U_3Si blanket consists of 600 helium-cooled modules.

TABLE 1-2
(Sheet 1 of 2)

FUSION FISSION HYBRID STUDIES
GENERAL PARAMETERS COMPILATION

Type	Units	Laser	Tandem Mirror Hybrid	Tokamak	Mirror Hybrid Y-Y	Laser Solenoid 1st Gen	Linear Theta Pinch	E- Beam	LMFBR	LWR	HTGR
Laboratory	-	LLL/BEC	LLL	W	LLL-GA	MNW	Los Alamos	Sandia	W Phase II	PWR	-
Fis Blanket	-	Depl U	233 U-Th	U _{nat} C	U ₃ S ₄	Depl U	ThC/Graph	Depl U	Depl UO ₂	UO ₂	-
Coolant	-	Na	Na	He	He	He	He	Na, Li	Na	Water	He
Fusion Power	MWe	850	260	760	390	-	-	720	-	-	-
Thermal Power	MWth	4000	1760	3000	3600	4000	40,000	3440	2600	3425	3000
First Wall Current	MW/m ²	2-1.3	2.8	1.55	2	2.4	-	1.3	-	-	-
Q Plasma Amplification	-	3.3	1.8	.92-1.25	.63	1.15	.0165	18	-	-	-
Major Radius or Length	Meters	5 m F/W Rad.	27 m Lth	4.45 m Rad	3 m Rad	250 m Lth	1 km Lth	5 m Rad 13 m Height	-	-	-
Minor Rad.	Meters	-	-	.9 m	-	-	-	-	-	-	-
Annual Fis. Produc.	kg/yr	2450/Pu	1000/U ₂₃₃	1800/Pu	1900/Pu	1800-2800/ Pu	1110/U ₂₃₃	2041/Pu	369/Pu	.128/ MWth	-
Net Electrical Output	MWe	1195-1215	500	935 gr	535	542	9500	1090	944	1139	1067
Pulse Duration	-	-	-	75 sec on 15 sec off	-	-	-	-	-	-	-
Fuel	-	-	-	-	-	-	-	-	Pu ₂	UO ₂	UC ₂ ThO ₂
Magnetic Field Strength	T	-	3T	-	8T max	30T	-	-	-	-	-
Laser/Injection Power	MJ/MW	-	-	380	625	15.4 MJ _c	-	4.3 MJ	-	-	-
Blanket Energy Mult	-	7.15	-	6.0	8.8-18	7.2	30	6.0	-	-	-
Tritium Brd. Ratio	-	-	-	.75	1.05-1.42	-	1.2	-	-	-	-
n _T	s/cm ³	-	-	-	2x10 ¹²	4x10 ¹⁵	.8x10 ¹³	-	-	-	-
Field Coil	-	-	-	Nb ₃ Sn	NbTi	Nb ₃ Sn NbTi	-	-	-	-	-
First Wall Material	-	Graphite Moly	-	-	-	-	-	S.S.	-	-	-

TABLE 1-2
(Sheet 2 of 2)

FUSION FISSION HYBRID STUDIES
GENERAL PARAMETERS COMPILATION

<u>Type</u>	<u>Units</u>	<u>Laser</u>	<u>Tandem Mirror Hybrid</u>	<u>Tokamak</u>	<u>Mirror Hybrid Y-Y</u>	<u>Laser Solenoid 1st Gen</u>	<u>Linear Theta Pinch</u>	<u>E- Beam</u>	<u>LMFBR</u>	<u>LWR</u>	<u>HTGR</u>
First Wall Coolant	-	Li	-	-	He	He	-	Li	-	-	-
Initial Pu Requirement	kg/MWt/ yr	0	0	0	0	0	0	0	.684	1.403	-
Fusion Blanket	-	50% Li	-	-	LiH	-	Li	Nat.Li	-	-	-
Fusion Blanket Coolant	-	Li	-	-	He	He	-	Li	-	-	-
LWR Support Ratio	-	5.4	-	3.7	4.2	4.1	5.5	6.0	.83	-	-
Recirculation power	-	.12	.3	.7	.53	.5	.44	.1	.095	-	-

TABLE 1-3
(Sheet 1 of 2)

FUSION FISSION HYBRID STUDIES
COMPARATIVE CHARACTERISTICS

<u>Present Status</u>	<u>Laser</u>	<u>Tandem Mirror</u>	<u>Tokamak</u>	<u>Y-Y Mirror</u>	<u>Laser Solenoid</u>	<u>Lin θ Pinch</u>	<u>E-Beam</u>	<u>LMFBR</u>	<u>LWR</u>	<u>HTGR</u>
Generations to demonstration size	1 gen	1 gen	1 gen	1 gen	3 gen	2 gen	1 gen	-	-	-
$Q = \frac{\text{Power Out}}{\text{Power In}}$	High	Low	Low	Low	-	-	Low	-	-	-
Recirculating Power	Low	High	High	High	-	-	Low	-	-	-
Major Problems	1) Q value not supported by calc.	1) Untested	1) Confinement not well understood	1) Heating plasma	-	1) $\text{TH-}^{233}\text{U}$ blanket 2) Large power	1) Transport over long distance	-	-	-
	-	-	2) Fueling	-	-	3) Poor breeder	-	-	-	-
$n_i, \text{ s/cm}^3$	-	-	10^{11}	10^{10}	-		-	-	-	-
Neutrons	10^7	-	-	-	-	-	10^7	-	-	-
Advantages	-	-	-	-	1) Heating understood	1) Solutions exist for heating and radial confinement	1) Successful pellet heating & electric beam generating 2) Very high efficiency	-	-	-
Required Physics Research	1) Layered pellets semi-isotropic heating		1) Better confinement in low density devices	1) Stabilize plasma without cold plasma		1) End Loss	1) Beam transport	-	-	-
Technology Development Requirement	1) Pulse power 2) Large laser		1) Hi- Energy region beam 2) Nb_3Sn superior 3) Pellet injection	1) Nb_3Sn superior - -	1) Pulse power - -	1) Pulse power - -	1) Repetition rate - -	- - -	- - -	- - -

TABLE 1-3
(Sheet 2 of 2)

FUSION FISSION HYBRID STUDIES
COMPARATIVE CHARACTERISTICS

<u>Present Status</u>	<u>Laser</u>	<u>Tandem Mirror</u>	<u>Tokamak</u>	<u>Y-Y Mirror</u>	<u>Laser Solenoid</u>	<u>Lin Θ Pinch</u>	<u>E- Beam</u>	<u>LMFBR</u>	<u>LWR</u>	<u>HTGR</u>
Blanket Problems	1) Explicit neutron calculations required 2) Present survey results must be greatly extrapolated	1) Survey neutronic calculations adjusted so that reactor has reasonable performance range	1) Lack of research with small beam-driven reactors 2) Large void fraction 3) Complicated geometry 4) Lack of realistic neutronic modeling	-	-	1) Small, thick magnetic solenoid degrades neutron performance 2) Survey results cannot predict hybrid blanket performance 3) Multiple linear plasma concepts must be calculated explicitly	-	-	-	-

- Tandem Mirror Hybrid

A tandem mirror reactor consists of a long linear solenoid whose ends are "plugged" by using two minimum-B mirrors. A fusion electric tandem mirror reactor design has been developed at Lawrence Livermore Laboratory. Neutral-beam injection into the end-plugs is used.

- Linear Theta-Pinch Hybrid

The theta-pinch fusion reactor concept involves a rapidly pulsed reactor in which a high density plasma and thermonuclear ignition of the plasma is obtained by a fast-rising magnetic field in a theta-pinch geometry. A fusion-fission hybrid design based upon the theta-pinch concept has been studied at Los Alamos Scientific Laboratory. The device is one kilometer long and has a ${}^7\text{Li}$ - ${}^{232}\text{Th}$ - ${}^{233}\text{U}$ blanket, and helium coolant is used.

- Laser Solenoid Hybrid

One concept is the Laser Heated Solenoid Hybrid (LHSH) which has been proposed and developed by Mathematical Sciences Northwest, Inc. The laser heated solenoid concept is similar to the theta-pinch concept except that it substitutes axially directed laser heating of the plasma for the shock-heating phase of the latter. The blanket consists of depleted uranium with no initial ${}^{239}\text{Pu}$ charge.

- Laser-Driven Hybrid

Conceptual designs of laser-driven (ICF) hybrid reactors have been reported by Lawrence Livermore Laboratory (LLL) with the Bechtel Corporation and the Westinghouse Corporation. The former design is optimized for fissile fuel production and the latter is optimized primarily for power generation. The LLL-Bechtel design consists of a depleted uranium blanket and is cooled with liquid sodium.

- Particle-Beam-Driven Hybrid

Particle-beam-driven hybrid (PBDH-relativistic electrons or light ions) are closely related to the laser-driven hybrids (LDH). The main difference is that particle-beam generators are considerably more efficient than lasers allowing lower pellet gain and yields for PBDH as compared to LDH. The largest particle-beam fusion program in the United States is carried out at the Sandia Laboratories in Albuquerque, New Mexico. In a Sandia-Bechtel design, either thorium or depleted uranium is used in the fission blanket and liquid metal cooling. In addition, there is a lithium blanket external to the fission blanket.

The major areas of concern in realization of the hybrid's potential are; fusion-fission hybrid technological development, safety requirements impact and overall plant reliability, and prevention and control measures required to avert diversion of special nuclear materials for weapons manufacture.

In the technology area, a basic question exists in the selection of the fusion driver for the hybrid machine. Current opinion favors the concept of using the hybrid primarily as a fissile-fusile fuel factory. The fusion driver is seen primarily as a neutron source, but although relaxation of the fusion plasma conditions is possible, current experimental conditions do require improvement to achieve neutron fluxes for fuel production. As potential fusion drivers for the subcritical fertile blanket, several quite different fusion machines, presently in the conceptual and experimental stages, use the principle of magnetic confinement of the plasma. There are, also, at least three reported inertial confinement devices under active investigation. It is improbable that all can economically be taken to the development level. Moreover, the principal direction of effort will be dominated by the potential for realizing the goal of fusion electric power production. In this review of technological problems, therefore, attention has been directed generically toward magnetic confinement and specifically to the Tokamak machine, as typifying the status of fusion drivers and the recognized problems. However, as the physics of laser fusion, electron-beam, and ion-beam fusion drivers mature, inertial confinement fusion devices may become viable hybrid choices. Tables 1-2 and 1-3 compare the currently reported scientific-technological position of a number of fusion-fission hybrid parameters and comparative characteristics. Technical assessments of the FFH reactor concepts are presented synoptically in Table 1-4 for the generic magnetic confinement systems and Table 1-5 for the generic inertial confinement systems. These tables indicate the critical problems, the required level of solutions, and kinds of programs required for achieving the desired solutions.

TABLE 1-4
MAGNETIC CONFINEMENT FUSION-FISSION HYBRID REACTORS
SYNOPTIC TECHNICAL ASSESSMENT*

Component or System	Technical Problems	Solution Needed**	Suggested Program
	Description	<ul style="list-style-type: none"> ●Research ●Development ●Demonstration 	
Fusion Driver	- Uncertainties in plasma performance	Demo.	Demonstration of appropriate plasma parameters
	- Plasma stability control		Development of advanced concepts (Tokamak Doublet; Tandem Mirror) and further data from present concepts (e.g., TFTR)
	- Radiation damage to materials	Dev.	FMIT and Engrg. and Materials Test Reactor
	- Superconducting magnet technology	Demo.	Development of new SC materials
	- Neutral beam injection	Dev.	Beam development from TFTR, MX and beyond
	- First wall integrity	Demo.	Structural integrity tests
	- Plasma divertor	Dev.	Tests of Divertor and Collector technology and currently planned Tokamak program
	- Tritium handling	Dev.	TSTA and Divertor/Collector Expts.
	- Plasma impurity control	Dev.	(See comments on plasma divertor)
	- Magnets	Dev. }	Much more in-depth conceptual design effort for all these systems
	- Plasma exhaust system	Dev. }	
Tritium Breeding Blanket	- Tritium breeding blanket design	Dev. }	Incorporate in a Hybrid Engrg. Test Facility but studies are needed to determine where this best fits in program (i.e., initial operation versus upgrade)
	- Tritium recovery	Dev. }	
Fission Blanket	- Blanket neutronics		Computer analysis of blanket configuration and determination of optimum fuel element design; more in-depth conceptual design effort is required.
	- Blanket design	Dev.	In-depth design effort and development programs
	- Radiation Damage	Res.	FMIT and HETF
	- Thermal and mechanical fatigue due to cyclic operation	Dev.	Irradiation materials data from FMIT and HETF
	- Remote maintenance	Demo.	Much more in-depth conceptual design effort as a means to identify alternate approaches and programs needed
	- Fuel cladding	Dev.	Irradiation materials data from FMIT and HETF
	- Remote handling system	Dev.	Should be an integral part of more detailed conceptual design effort
<p>* This table is a condensed version of Table 6-1 in the "1978 Source Book for Fusion-Fission Hybrid Systems" emphasizing critical items.</p> <p>** Research, Development and Demonstration have been abbreviated, respectively.</p>			

TABLE 1-5
INERTIAL CONFINEMENT FUSION-FISSION HYBRID REACTORS
SYNOPTIC TECHNICAL ASSESSMENT*

Component or System	Technical Problems	Solution Needed**	Suggested Program
	Description	●Research ●Development ●Demonstration	
Laser Systems	- Laser performance	Res.	
	- Current laser system efficiency is too low	Res.	Development or discovery of lasers at proper wave length with efficiency greater than 10% of acceptable cost
	- Low operation availability of laser pre-amplifiers and amplifiers	Res.	
	- Laser optics technology	Dev.	Testing of materials at high irradiance
	- Last mirror degradation	Dev.	Tests to establish operating and maintenance procedures (cleaning, regrinding, recoating, replacement)
	- Power supply quality critical to control laser frequency and coordination with pellet in reactor	Dev.	Integrated laser systems development program needed in technology areas to give performance suitable for commercial hybrid applications
	- Laser preamplifier and amplifier	Res.	In-depth conceptual design effort and development program
	- Optical equipment	Dev.	
	- Reliability of 10,000's of components	Demo.	
Fusion Driver	- Uncertainties in laser light interaction with the D-T pellets	Dev.	Existing Shiva, Antares programs
	- Uncertainties in D-T pellet physics, especially high-gain pellets	Demo.	Demonstration of scientific feasibility and sufficient pellet gain to compensate for attainable laser system efficiencies
	- Pellet fabrication technology	Dev.	Develop low-cost automated microminiature pellet production
	- Pellet design, computation, yield, and output spectra	Res.	
	- First wall design	Res.	An integrated program for reactor cavity design (not just first wall or vessel) to insure adequate containment and to provide an integrated facility for blanket fuel elements
	- Pellet injection	Demo.	
	- First wall cooling	Demo.	
	- First wall materials	Dev.	Obtain irradiated properties data from FMIT, HETF
	- Tritium recovery and handling system	Dev.	Much more in-depth conceptual design effort to form the basis for assessment of equipment and construction as well as program to insure acceptable tritium containment
Tritium Breeding Blanket	- Tritium breeding blanket design	Dev.	Incorporate in a HETF but studies are needed to determine where this best fits in the program (i.e., initial operation vs. upgrade)
	- Tritium recovery	Demo.	
Fission Blanket	- Blanket neutronics		Computer analysis of blanket configurations and determination of optimum fuel element design
	- Blanket design	Dev.	Much more in-depth design effort
	- Radiation damage	Res.	FMIT and HETF
	- Thermal and mechanical fatigue due to cyclic operation	Dev.	Determine applicability of existing fatigue data without neutron flux; irradiation materials data from FMIT and HETF
	- Remote maintenance	Demo.	
	- Fuel element cladding	Dev.	Irradiation materials data from FMIT and HETF

* This table is a condensed version of Table 6-2 in the "1978 Source Book for Fusion-Fission Hybrid Systems" emphasizing critical items.

** Research, Development and Demonstration have been abbreviated, respectively.

* This table is a condensed version of Table 6-2 in the "1978 Source Book for Fusion-Fission Hybrid Systems" emphasizing critical items.

** Research, Development and Demonstration have been abbreviated, respectively.

1.5.1 The Fusion Driver

The fusion driver is primarily viewed as a neutron producer, in terms of implementing the hybrid as a fissile-fusile fuel breeder. Previously, it was noted that a significant relaxation of the constraints for fusion electric plasma conditions would still permit the fusion driver to provide neutrons at adequate levels for fissile and fusile fuel breeding. In order that the magnetic confinement machines achieve levels of neutron production useful to the breeding option require further upgrading of capability. Some major engineering and technological advances required in the development of the hybrid are in the areas of: superconducting magnet designs, associated cryogenic systems, injection systems for the fusile fuels to be burned in the plasma, and reaction-products removal systems, efficient fusion reactor heating methods (ohmic, RF, neutral beams, etc.) for magnetic confinement fusion drivers, and efficient laser sources and pellet design for high power gains in terms of inertial confinement fusion drivers. Also, the effects of short duration pulses on the fertile blanket material is relatively undetermined. The duration of subsequent fission reaction production of substantial neutron fluxes is still very short. The next generation of fusion machines of the tokamak type is expected to operate cyclically, with a fusion "burn-time" of the order of 50-70 seconds followed by a purge time for the removal of reaction products, of 10-20 seconds. Thus, the neutrons for this machine would be fed into the blanket in pulses and the resulting fission reactions would also be cyclic.

1.5.2 The Fission Blanket

Detailed studies are required to define the neutronics in the area of the fertile blanket design for use in a practical hybrid system. The systems considered can include a number of options (solid block, pebble-bed spheres,

molten salts, or others). In the case of heterogeneous fuels, the blanket will consist of fertile materials properly encapsulated and supported by mechanical structures. All of these materials, however, need to be compatible among themselves with respect to the thermal radiation and coolant system flow conditions creating the blanket's physical environment, and they must be able to survive the blanket environment itself. These problems have been recognized, but they have not, as yet, been adequately studied at the experimental level of development. Planning for test facilities and test programs for the determination of materials capabilities is in progress.

The hybrid's reactor engineering may be more complicated than for a fusion electric device. However, this depends on the requirements of the blanket design. Blanket design can be advanced from fission fuel experience, providing blanket configuration, structural support systems, coolant systems, and control systems are adequately defined. Additionally, operation and maintenance access within the constraints of unique fusion reactor geometries and attendant environment must also be defined.

The type of fission converter used may affect the design of the blanket. This is particularly the case for a hybrid designed to utilize the proliferation-resistant "refresh" concept. For this case, the hybrid design is controlled by the optimization of both the hybrid reactor and the satellite converters. With the use of reprocessing, the hybrid reactor will be designed to optimize performance and economics, just as the fusion electric reactor eventually will be.

1.5.3 The Hybrid Materials Engineering

The behavior of materials subjected to high energy inputs is of major engineering concern to both the fusion electric reactor and the hybrid. Energy inputs

range from 0.5 to 10 MW/m² (depending on the fusion device) as produced by photons and both charged and uncharged particles. Macroscopic as well as microscopic changes are induced under such conditions which can degrade the performance of the materials. Some of the work related to fission reactor experiments at very high burnups may be applicable to this problem. The fertile materials: lithium, uranium and thorium needed for the blanket require the definition of chemical and physical forms which can provide adequate performance under these conditions. The "refresh" concept, to be successfully implemented, requires that the fuel and cladding materials withstand the neutron environment of the hybrid for longer periods of time than for reprocessed fuel (at least twice as long). This is in addition to the normal burn-up exposure anticipated in the advanced fission converters.

To facilitate timely deployment of the hybrid, engineering support activities should begin now. Effort should be devoted to blanket configurations and neutronics, system design for remote disassembly and handling of the first wall and after-blankets, cooling system design, fusion input energy equipment, and the wide range of materials behavior in the high energy neutron field, detailed conceptual designs that can help formulate firm capital, operating and maintenance costs.

Environmental concern because of tritium inventories is raised for both the hybrid and fusion electric devices. Also, heat sink requirements and potential biological hazards from such high energy equipment as lasers and superconducting magnets are also major areas of concern.

1.5.4 The Hybrid Safety Considerations

The hybrid contains fissile material, fission products, and activated materials. Therefore, it will be of greater safety and environmental concern than the fusion electric devices. The hybrid reactor will be subject to safety reviews as considered appropriate. Licensing procedures, similar to those for LWRs and LMFBRs will also be implemented for the hybrid, as applicable.

The fusion portion of a hybrid reactor may be smaller than that for a fusion electric reactor of equal gross MW_{th} output as a result of the energy contribution from the fission reactions. This may require smaller tritium inventories and reduced amounts of stored energy in the magnetic and/or laser input energy equipment. The hybrid offers a distinct advantage over other fission breeders in that the blanket is a subcritical assembly. The hybrid is potentially vulnerable to melt down of the fissile-fertile blanket due to residual fission product after-heat if the blanket heat-removal system fails. However, except possibly in certain modes of the proposed "refresh" option, this cannot result in secondary criticality which is the most severe accident projected for the LMFBR.

The hybrid offers several unique subjects for safety analysis such as: enhanced requirements for in-service inspection in the presence of adverse environments; the high concentrations of stored energy; the preservation of isolation integrity by isolation of beam ports; the disposal of stored magnetic energy upon sudden loss of coil power; in the case of magnetic confinement the loss of cryogenic coolant to the coils; liquid metal fires; and, the presence of hazardous substances.

The hybrid's licensing questions seem to be not any more stringent with regard to the fertile-fissile blanket than those that exist now for an LWR. The blanket initially is not composed of fissile materials; and, in itself, cannot produce self-sustaining fission reactions, since it is designed to remain subcritical. The problem presented by the tritium fuel inventory of the fusion device and of tritium bred in the blanket must be dealt with for both the fusion electric reactor and the hybrid.

The fusion electric systems, of course, do not present problems associated with the fissile fuel cycle and the potential of diversion and proliferation of nuclear materials for weapons manufacture. However, the hybrid is a fissile fuel producer, and thus security measures to avert nuclear weapons proliferation must be taken in the event of deployment. The hybrid fertile blanket design may be influenced by the fueling requirements of its satellite fission converter reactors. In an optimized fuel cycle it might be possible to design fuel elements for compatible neutronic and heat transfer performance in the hybrid blanket and in the satellite reactor. The "refresh" concept virtually mandates this level of optimization, but, as noted earlier, development of highly radiation-damage resistant fuel forms and claddings are necessary.

For fuel cycle flexibility, chemical reprocessing of the blanket, for recovery of the fissile fuel, maximizes the benefits of the hybrid. The recovered fissile fuel can thus provide the annual makeup requirements of any of its satellite converters rather than supplying the whole fuel element, as in the case of the refresh cycle.

Production of the pure, separated, thermally-fissile materials: ^{233}U , ^{235}U , and ^{239}Pu , in areas potentially subject to unauthorized removal, is the key

concern in most weapons proliferation scenarios. A relatively large number of options do exist, however, by which fissile materials can be controlled and/or "denatured", in order to avert clandestine weapons manufacture. This large variety of options constitutes a problem whose resolutions effectively details the specifics of the fertile blanket design. Consequently, for work to go forward in the hybrid blanket designs, decisions as to the preferred methods of control are needed at an early date. This weapons proliferation can be minimized or avoided by "denaturing" the fissile materials while they are under satisfactory controls. This denaturing can be done by diluting the fissile materials:

- with isotopes of the same element which are not subject to thermal fission: e.g., additions of ^{238}U to ^{233}U and ^{235}U ;
- with other non-fissile but chemically compatible elements; e.g., additions of ^{232}Th to ^{233}U , ^{235}U , and ^{239}Pu ; or ^{238}U to ^{239}Pu ; or,
- with highly radioactive fission products deliberately added or simply not removed in reprocessing.

Other approaches include:

- co-separation of non-fissile ^{238}U with ^{239}Pu , or with ^{233}U bred from ^{232}Th , and,
- co-location, in a suitably controlled energy center, of the reprocessing, fuel element fabrication, and perhaps, even the satellite fission reactors.

The hybrid is adaptable to all of the above non-proliferation measures. It is particularly adaptable to an energy center concept because it is a fuel producer. The hybrid offers an opportunity for implementing the "refresh" fueling concept in which the spent fuel elements from a satellite reactor are directly lodged in the hybrid blanket and the fertile material is irradiated until the level of fissile material needed for the operation of the converter

is reached. This scheme, in which there is no separation of the fissile material as a pure product, is considered highly resistant to weapons proliferation. After one or more such exposures for "refreshment", the fuel element is sent to storage. It is important to note that the recent studies indicate the "refresh" cycle is adaptable to both advanced converter reactors (HTGR, etc.) and LWR converters.

1.6 STRATEGY FOR RESEARCH, DEVELOPMENT AND DEPLOYMENT OF HYBRIDS

Factors defining the need for the hybrid and the timing have been previously discussed. Potential major technical and non-technical considerations that must be addressed to make a hybrid demonstration plant a reality have been reviewed. What remains is the question of designing a development program for the hybrid that will provide a commercial hybrid reactor to a timetable in anticipation of future needs. The major savings in the fusion electric development program associated with the hybrids are:

1. The fuel producing hybrid can be designed to relaxed plasma physics conditions which could be achieved before those required for fusion electric; and,
2. Deployment of the hybrid particularly benefits from its use as a fuel producer, and, therefore, the time for significant energy contribution of the hybrid can be earlier than other technologies which directly replace some existing methods of electric generation.

The major addition to the program time arises from the need for nuclear safety licensing review. A possible RD&D timetable is presented on page 1-34 and depicted in Figure 1.6. This timetable addresses the evolution from scientific engineering demonstration through commercialization.

Figure 1.6 Fusion-Fission Hybrid Development and Deployment Timetable

The rate of success in meeting this timetable could greatly influence industrial decision makers in terms of future commitments to: LWRs and advanced converters, added facilities for separative work, exponential uranium exploration, reprocessing facilities as well as manufacturing for commodities and components.

<u>Timetable Summary</u>	<u>Fusion-Fission Hybrid</u>
Scientific feasibility demonstration	1982
Decision to proceed with engineering demonstration	1983
Start of operation of engineering demonstration	1993
Decision to proceed with prototype demonstration	1989
Start of operation of prototype demonstration	2000
Commitment to first commercial installation	1995
Startup of first commercial installation	2006

Some program planners approach this schedule with caution because of their previous experience and therefore add five to ten years for contingency.

1.7 OBSERVATIONS AND CONCLUSIONS

A review of the work on fusion-fission hybrids to date leads to the following conclusions:

1. The fusion-fission hybrid may be developed and deployed before the fusion electric device because:
 - a) The fusion plasma physics requirements are nearly in hand compared to fusion electric.
 - b) The fission blanket technology can benefit from current fission reactor technology.

- c) The great market potential associated with existing and future satellite converters.
2. Early deployment of fusion-fission hybrids will require:
 - a) The nuclear safety and environmental licensing requirements and interveners' actions do not extend the engineering and commercial prototype demonstration projects to such an extent as to compensate for the fusion electric development lag time.
 - b) The major material evaluation activities and engineering activities begin in the immediate future and are successful.
 3. The fusion-fission hybrid can have an operating commercial prototype by the year 2000 A.D. with the starting of the first commercial units by 2006 A.D. if a very aggressive development program is pursued.
 4. Although the hybrid's deployment will be affected by learning curve limitations, the hybrid will rapidly impact the energy sector due to its high fuel production rate. Fissile fuel for substantial numbers of burner reactors could be in production within a decade from commercial availability.
 5. This timetable of deployment in the early decades of the twenty-first century is achievable but substantial work in the technical, engineering and economic aspects is needed to confirm its economic and political desirability.
 6. The relationship of the hybrid to its satellite reactors controls the ultimate product cost to a significant degree.
 7. It is premature to attempt to exactly define the relationship of the hybrid and the LMFBR to the needs of the nuclear energy marketplace because of the large uncertainties in the capital cost of the hybrids and the political cost of the LMFBRs.
 8. The hybrid can be highly proliferation-resistant under a "controlled" reprocessing scenario and has a significant advantage because it forms the basis for the development of the proliferation resistant "refresh" concept.
 9. The hybrid dedicated to fissile-fuel production for electrical and industrial reactors could be the first step in the general deployment of fusion power as technological development permits. The deployment sequence envisioned consists of a hybrid for producing fuel and electricity followed by a fusion electric device and finally a fusion-thermal device for the industrial and synfuels reactors.

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