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FUSION UTILIZATION PROJECTIONS IN THE UNITED STATES ENERGY ECONOMY

J.R. POWELL AND J.A. FILLO

MASTER

November 1979

DEPARTMENT OF NUCLEAR ENERGY

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EXECUTIVE SUMMARY

Energy from fusion can help meet U.S. energy needs through three major applications:

1. Electric generation
2. Synfuels/chemical production
3. Fissile fuel production

Electric generation has been the role traditionally considered for fusion energy. Base loaded fusion reactors would supply major blocks of power, on the order of 1000 MW(e), to the electrical grid in a manner similar to the existing large coal-steam and nuclear power plants.

The role of fusion in synfuels and chemical production has only recently been considered in detail. Fusion energy can be used to split water to hydrogen and oxygen. Hydrogen has many potential energy related uses--directly as a fuel for industrial processes, as a feedstock for chemical production (e.g., ammonia) or metal refining (e.g., H-iron), as a blend with natural gas for space or process heat, or as feedstock for the production of synthetic hydrocarbon fuels.

In the latter case, fusion hydrogen could be combined with carbon from coal, biomass, or atmospheric CO₂ to make a wide range of hydrocarbon fuels (e.g., methane, gasoline, oils, etc.). Fusion/coal symbiotic systems would permit the generation of hydrocarbon fuels with a large reduction in coal usage (a factor of 2 to 3, depending on product). This would greatly ease coal production and transportation constraints, reduce environmental emissions, and stretch coal reserves.

For the third fusion application, fissile fuel production, high-energy neutrons from the fusion plasma would interact with a surrounding fertile (U^{238} or Th^{232}) blanket to generate fissile material (Pu^{239} or U^{233}) to supply make-up fuel for a LWR economy. Each fusion-fission (hybrid) reactor could support 5 to 10 large [1000 MW(e)] LWRs, depending on fuel cycle and reactor design. Fission reactions in the blanket would make the total power level for the hybrid reactor an order of magnitude larger than the fusion plasma power, easing plasma confinement and energy multiplication requirements. Electric generation from hybrid reactors would probably be supplied to the electric grid.

Energy system supply and demand projections to 2040 AD have been derived from EIA (Energy Information Administration) studies. The EIA projections were selected as the most official U.S. government projections on future energy supplies and demand. Potential implementation rates are then developed for the different fusion applications, assuming commercialization in 2000 AD. For the case where fusion growth rate is comparable with the historical growth rate for fission power, 500,000 MW(e) of fusion electric capacity would be operating by 2040 AD, ~34% of total U.S. electrical capacity. [A capacity of 500,000 MW(e) corresponds to 12 Quads per year of electricity production (1 Quad = 10^{15} Btu).]

Faster implementation rates appear possible if economic and other factors strongly favor fusion. However, technological factors (plant construction time, the learning curve, availability of trained workers, etc.) will at some point provide a limit to the maximum possible implementation rate.

Based on our judgment of the technical limits on fusion implementation, it appears that the maximum possible fusion capacity could be on the order of 10^6 MW(e) in 2040 AD, ~70% of the total U.S. capacity.

The average growth rate for U.S. electrical production in the 2000 to 2040 period is expected to be relatively low, on the order of 2% per year. This is considerably smaller than the ~ 7% per year growth rate experienced in the U.S. during the last few decades.

The normal lifetime for power plants is 30 to 40 years, corresponding to a replacement rate of ~ 3% per year on existing capacity. Thus, if fusion is to supply a significant portion of U.S. electrical energy by 2040 AD, a large portion of the new and replacement plants in the 2020 to 2040 period will have to be fusion reactors. To achieve the maximum implementation rate examined in this study, it might also be necessary to phase out some existing plants before the end of their normally scheduled life.

Coal and nuclear power (in roughly equal amounts) are expected to comprise virtually all of the U.S. electric capacity at the time that fusion plants would come on line. Both will be mature, optimized technologies; to replace them, fusion electric plants will have to exhibit substantial economic and/or environmental benefits.

Hybrid implementation has not been explicitly considered in this study. In its expected role as a primary fissile fuel supplier to LWR's, the hybrid offers an alternative to a breeder economy, permitting LWR's to operate for a very long period into the future. In this role, the hybrid would be implemented at the rate necessary to sustain the LWR portion of the U.S. electrical economy. A relatively small number of hybrid reactors would be able to sustain the LWR economy because of the large number of LWR's that could be supported by a single hybrid reactor. Approximately 50 to 100 hybrid reactors would be required by 2040 AD, and this implementation level should be readily

achievable. The principal factor affecting hybrid implementation will be the relative economics of an LWR/hybrid system as compared to a fission breeder system.

Considerably different factors will effect the implementation rate for fusion synfuels. Conventional oil and gas supplies, both domestic and imports, will be rapidly decreasing in the post 2000 period, forcing the use of enhanced recovery methods and massive development of synthetic fuels. In the EIA projections, the synthetic liquid and gaseous fuels would be obtained using coal-only processes, with a very large increase in coal usage (almost an order of magnitude by 2040, according to BNL extrapolations of EIA trends at 2020 AD).

Coal production constraints and adverse environmental effects [toxic emissions (solids and gases), water demands, and land spoils] associated with large scale coal usage should create a favorable situation for alternate approaches to synfuels, such as fusion.

If the implementation rate for fusion synfuel plants follows historical experience for the fission power industry, 40 Quads per year of fusion H_2 could be produced in 2040 AD, assuming commercialization of fusion synfuels in 2000 AD with two initial plants. Fusion H_2 would then correspond to 61% of the total portable fuel production in the U.S., and 70% of the "non-standard" fuel production (synthetic liquid and gaseous fuels, imports, and enhanced recovery).

If fusion synfuels were implemented at the maximum possible rate, based on our judgment of technological limiting factors, 55 Quads per year of fusion H_2 could be produced in 2040 AD, corresponding to 83% of the total portable fuel production in the U.S., and 95% of the non-standard fuel production.

Development of fusion synfuels would also considerably reduce the need for large increases in U.S. coal production. With coal-only synfuels, coal production in 2040 would have to be 120 Quads per year to meet projected U.S. energy demands, which is eight times current (1978) U.S. production levels. If fusion synfuels are implemented at a growth rate similar to that experienced by the fission reactor industry, coal production would still have to increase, but production in 2040 would be held to 80 Quads per year, a factor of 5.5 larger than current (1978) production. With maximum implementation of fusion synfuels, coal production in 2040 would be only 50 Quads per year, a factor of 3.5 larger than current production.

Moderate implementation rates for fusion synfuels result in a flattening of coal production after 2020 AD instead of progressively increasing production. Maximum implementation of fusion synfuels, on the other hand, results in a strong drop in coal production after fusion synfuels fully come on line, around 2010 AD.

The present fusion development program is directed towards electric applications. This technology will in a large part be directly transferable to synfuel and fissile fuel production, though the latter two applications require somewhat different blanket design approaches and materials. Some additional process technology development for synfuel production will also be required.

Research and development on fusion synfuels technology should be started soon, if it is desired to achieve commercial status in the first generation of fusion reactors. There does not appear to be any serious obstacle to achieving such capability, however, if appropriate R & D is undertaken to test process technology and to develop the particular materials needed for synfuel blankets. Generally, process R & D will not require fusion reactor facilities.

Application of fusion reactors to fissile fuel production will require R & D on blanket design and development of blanket materials, particularly fission fuel elements, that will be capable of operating under the radiation damage conditions expected for fusion blankets. It appears likely that hybrid reactors can be developed in a time comparable to that required for pure fusion reactors; however, the special safety and licensing concerns associated with the large inventory of fission products, as well as the wide range of potential new accident conditions that would have to be examined, could significantly delay the commercialization of hybrids.

The test facilities now being considered in the fusion program (i.e., TFTR, FMIT, ETF, etc.) should be suitable for the R & D related to the applications discussed above. For synfuels R & D, for example, TFTR could be used to test neutronics performance of mockup synfuels modules, including tests of the fraction of fusion energy that could be delivered at high temperatures; FMIT could be used to test the radiation damage performance of synfuel blanket materials at high temperatures (e.g., ceramics like Al_2O_3 or ZrO_2 , which are candidate materials for producing high temperature process streams); and ETF could be used to test prototype synfuel blanket modules under actual fusion reactor conditions.

Alternate fusion concepts and fuel cycles for the three principal applications have been examined from the viewpoint that if they prove feasible, do they provide the output characteristics needed for a practical reactor system?

The DT fuel cycle appears to be the best choice for synfuels and fissile fuel production. In the first application, the deep penetration capability of 14 MeV neutrons from the DT fusion reactions is necessary in order to achieve the high

process temperatures needed for efficient hydrogen production. In the second application, 14 MeV neutrons are required in order to achieve high fissile fuel production rates. [The catalyzed DD fuel cycle may be acceptable for hybrid reactors, though more investigation is needed of this possibility.] For electric production any fuel cycle should be acceptable, provided it is technically and economically practical.

Most fusion confinement approaches appear suitable for synfuel production, providing they are technically and economically practical. Low output power approaches, like the Field Reversed Mirror, probably would not be economically optimum, however, since large plant powers will be required, on the order of several thousand megawatts.

1. INTRODUCTION

The development of fusion power will proceed through the three stages characteristic of any new energy source:

- a. Scientific feasibility
- b. Technological practicality
- c. Commercialization

The scientific feasibility of fusion is expected to be demonstrated in the next few years by a variety of large experiments currently under construction or planned (TFTR, JET, JT-60, MFTF, etc.). Tokamaks will probably be the first magnetic confinement approach to achieve this goal, but other promising confinement approaches are being followed, including mirrors, EBT's, reverse field pinches, etc.

Substantial effort is also being carried out on inertial fusion using lasers and ion beam drivers. Demonstration of the scientific feasibility of ICF is likely to follow that of magnetic fusion since the ICF program has not been in place as long, and funding levels are substantially lower than for magnetic fusion. For this paper we primarily focus on magnetic fusion; the types of applications appropriate to magnetic fusion can also be met by inertial fusion, though the technology details may be different.

After scientific feasibility has been demonstrated, technological practicality must be established by sustained operation of near full-scale reactor systems. These reactors will have to test the features needed in full-scale commercial reactors, such as radiation resistant structural materials, breeding and recovery of tritium from the blanket, generation

of coolant temperatures high enough to be useful for power generation and/or chemical processes, plasma impurity control, long time burn capability, etc. Various design concepts have been discussed over the past few years for demonstrating technological practicality, including ERPs, TNSs, ETF, INTOR, etc. No commitment to a particular facility has yet been made, however, and may not be until after scientific feasibility has been demonstrated.

The final stage, commercialization, will require construction and operation of at least one prototype commercial reactor. Various design studies of such a DEMO reactor have been carried out. While not necessarily competitive, such a reactor should be close enough to a final commercial plant that technical and economic extrapolations are relatively small and can be made with a high degree of confidence.

The date for achieving commercial status will depend not only on the difficulty of the technical problems to be encountered, but also on what information and results are deemed necessary before commitments to new program steps are undertaken. For example, at one extreme the decision to start design of large scale experimental reactors to test technological practicality could be made before scientific feasibility was established; at the other extreme, it could be delayed until a number of plasma devices (using different confinement approaches) had successfully demonstrated scientific feasibility, with the best approach then chosen for the experimental reactor.

For purposes of this study, we have assumed an aggressive development program that achieves commercialization in 2000 AD. This will require some overlapping, with a start on an experimental reactor program before scientific feasibility is fully established, and a start on a DEMO reactor before the experimental reactor operates. The overlap period would be comparatively short (i.e., a few years), however; necessary design modifications could be made relatively simply and cheaply, but no major equipment changes should be required.

We have also assumed that each of the three principal fusion applications, i.e., electrical generation, synfuels production, and fissile fuel production by fusion-fission reactors (hybrids), could be commercialized by 2000 AD. Synfuel fusion reactors will be similar to those developed for electrical generation, with significant differences only in blanket design and materials. Generally, the process technology is external to the reactor. Development and testing of process technology at the pilot plant level will be required, but this can be carried out relatively quickly without fusion sources. It thus appears that commercial fusion synfuel reactors could be operating at approximately the same period as fusion electric reactors, given a program commitment to develop the associated process technology and materials. Until recently, principal focus has been on fusion reactors for electrical production; the importance of synfuels production is becoming much more appreciated, however.

The commercialization of hybrid fusion-fission reactors will require consideration of many safety and licensing questions not normally associated with fusion reactors, such as possible critical configurations during accidents, fission product release, loss of coolant accidents, etc. Even if technical development of hybrids could be achieved by the year 2000, a substantial delay might be required to resolve safety and licensing issues before commercialization.

The suitability of the alternate fusion approaches for the various applications is considered in this study, insofar as they are compatible with the particular technology for each application. In the case of fusion synfuels production, for example, the primary requirement is for blankets with high temperature coolant capability. Most of the fusion approaches can meet this requirement, though not all (e.g., inertial fusion reactors with thick liquid walls [i.e., HYLIFE]). The issue of which fusion approach is best from the point of view of plasma engineering (i.e., heating, impurity control, magnetic field requirements, etc.) is not addressed, however.

2. APPLICATIONS OF FUSION ENERGY

Fusion energy has the potential for a variety of applications, including:

1. Electrical generation
2. Synthetic fuels and chemicals
3. Production of fissile fuel (Plutonium, U-233)
4. Process heat
5. Space heat

These applications could be met either with separate plants or multipurpose plants (e.g., hybrid fusion-fission reactors could produce both fissile fuel and serve as base load electrical plants, or pure fusion reactors could generate both synfuels and electricity). Multipurpose plants may ultimately be more economic; however, in this study we consider only single purpose plants, except for space heat applications (i.e., district heating) which would use reject heat from any fusion plant.

Fusion electric applications have received a great deal of attention; to date, all of the reactor reference designs (UWMAK 1, 2, and 3, the PPPL design, the GA DEMO, the EPR designs, Culham Mark 1, NUMAK, the Mirror Reactor designs, the ORNL DEMO, etc.) have assumed that the fusion energy would be used to generate electricity. In these studies, generation capacity typically has been in the range of ~ 1000 to 2000 MW(e), with the plant operating in a base load mode.

The power generation technologies considered in these designs are usually conventional steam cycles, with efficiencies on the order of 35 to 40 percent. As a rule, the unique potential of fusion for generating very high coolant temperatures is not utilized to achieve high power cycle efficiencies.

Fusion electric generation technologies are examined in more detail later in this study; however, cycle efficiencies on the order of 60 percent (fusion energy to electricity) appear possible using two temperature zone blankets, with the high temperature interior directly heated by neutron and gamma energy deposition.

The application of fusion energy to the generation of synthetic fuels and chemicals has received relatively little attention. There have been a few conceptual studies of various processes for generating hydrogen using fusion energy, but no detailed reactor reference designs have been made. This reflects the fact that, until relatively recently, liquid and gaseous fuels have been plentiful and cheap.

Figure 2.1 illustrates the range of fuels and chemical products that could be produced by fusion. The initial step for all products involves splitting of water molecules to generate H_2 and O_2 . Process technologies for hydrogen production are discussed in more detail later in this study; it appears that the very high process temperatures possible with fusion energy can be used to generate H_2 at high overall efficiencies, that is, 50 percent or greater.

The generated H_2 can be used directly as fuel for various end uses as proposed in studies of the "hydrogen economy", including industrial process heat, liquid H_2 fueled aircraft, and automobile transport (using metal hydrides or other devices to store H_2 fuel). H_2 can also be directly used to produce chemicals (ammonia) or metals (iron and steel by the H-iron process). Finally, hydrogen can be combined with carbon to produce synthetic carbonaceous fuels, including methane, methanol, gasoline, diesel fuel, and various weight

Figure 2.1. Fuels and Chemical Products from Chemical Energy.

oils. The source of carbon can be fossil (coal) or non-fossil (limestone, biomass, atmospheric CO_2). The oxygen co-product would also have many uses, including iron and steel manufacturing, power generation (MHD), and fuel production (coal gasification).

The role of fusion synfuels in the future U.S. energy economy is discussed in more detail in the following section; the potential importance of synfuel production for fusion is vividly illustrated in Table 2.1, however, using present (1977) energy use patterns. In order for fusion to supply one-half of present energy consumption for the various end-use demands, the number of fusion reactors generating synthetic fuels would have to be much larger, by a ratio of approximately 5 to 1, than the number generating electricity. In many instances, of course, substitution of electricity for liquid and gaseous fuels is possible; however in many cases it either is not possible (airplanes), or not technically or economically practical (automobiles).

Synfuel production has a significant advantage for fusion reactor operation, since the inherent storage capacity associated with the production of a storable product considerably eases the very stringent reliability requirements imposed by electrical production for the grid. First generation fusion reactors would not need to have the very high reliability associated with large base loaded electrical generation plants, if they were used for synfuel production.

The third application, fissile fuel production, has received considerable attention in the last few years, and a number of reference designs for both magnetic and inertial fusion hybrid reactors have been carried out. Fusion tends to be neutron rich and energy poor, while fission is the converse, i.e.,

TABLE 2.1
Fusion Synfuel Demand Potential

<u>DEMAND SECTOR</u>	<u>FUSION SYNFUEL PRODUCT</u>	<u>ENERGY DEMAND [1977 QUADS]</u>	<u># OF FUSION REACTORS TO SUPPLY 50% OF DEMAND SECTOR</u>
<u>Transport</u>			
Auto	H ₂ (Hydride) Gasoline Methanol	9.8	136
Truck, Bus	Methanol	6.2	86
Aircraft	Liquid H ₂ , Jet Fuel	2.2	30
<u>Industrial</u>			
Process Heat	H ₂ (Gas)	14.0	194
Iron and Steel	H ₂ (Gas)	2.0	28
Petrochemicals	H ₂ , CO ₂	4.4	61
<u>Residential & Commercial</u>			
Space, Hot Water Heat	H ₂ (Gas)	8.5	118
		Total	653
<u>Electricity</u>	-----	6.6	131

Conditions: Reactor Power = 3000 MW(th)
H₂ Production Efficiency = 50%
Plant Factor = 80%
Electrical Production Efficiency = 35%

neutron poor and energy rich. The total energy release per fission reaction is much greater than that of a fusion event (200 MeV vs. 20 MeV); however, the number of extra neutrons available above that necessary to keep the reaction going is much greater for fusion than fission. [Although fusion does not involve a neutron chain reaction, neutrons must be captured in a lithium blanket to generate tritium in the DT fuel cycle to replenish that burnt in the plasma.]

By placing suitably designed, highly subcritical blankets of fertile material (U^{238} or Th^{232}) around a fusion plasma, the 14-MeV fusion neutrons will cause fast fission reactions, generating extra energy and neutrons for breeding of fissile fuels (Pu^{239} or U^{233}). Typically, a fusion-fission reactor (per DT fusion) has about ten times the thermal output of a pure fusion reactor for the same fusion power release. It also generates approximately one net fissile atom per DT fusion (some additional fuel fissions in the blanket, providing part of the thermal energy generated by the reactor). With suitable blanket design, the reactor can be self-sufficient in tritium, producing as much in the blanket as is consumed in the plasma.

The fissile fuel produced in hybrid reactors can provide fissile fuel feed for operating nuclear reactors. Light-water reactors (LWRs), for example, have conversion ratios of ~ 0.6 , and require ~ 0.4 atom of fissile fuel makeup per atom fissioned. Assuming reprocessing with small losses (a few percent), 1000 MW(e) LWR thus requires ~ 350 kg/year of makeup fissile fuel. At present, this is supplied by enriching natural uranium and feeding new fuel to the reactor. With fuel reprocessing and recycle, one hybrid fusion-fission reactor could supply fissile fuel for 5 to 10 LWRs, depending on the fuel cycle (U-Pu or U-Th) and the hybrid characteristics.

Application of the fusion-fission concept assumes that the nuclear power industry will remain viable for many decades to come and that fuel reprocessing and recycle will be allowed. At present, reprocessing and recycle have been avoided because of concerns about proliferation of nuclear weapons capability. [The possibility of non-reprocessing fuel cycles in which fusion neutrons would pre-enrich or rejuvenate reactor fuel elements placed in hybrid blankets has been examined; however, such cycles do not appear very promising because of radiation damage and geometric considerations.] The application of hybrids would permit extending the use of LWR's indefinitely, since plentiful fertile elements (U^{238} and Th^{232}) would then be used to generate power. The need for fission breeders, such as the LMFBR, would then be forestalled. The use of hybrids would minimize the number of new technology plants that would have to be built, since one hybrid would supply a large number of LWRs.

While potentially important for the electric sector by maintaining an LWR economy, hybrids do not appear suited for producing portable fuels, other than by the low efficiency route of generating electricity for conventional low temperature electrolyzers. Hybrids are usually perceived as introducing fusion into commercial use before pure fusion devices, with the argument that initially low Q's (fusion power/injected power) or high capital costs for the fusion driver will not significantly affect the cost of fissile fuel product. Pure fusion reactors would then evolve from hybrids as plasma performance improved and capital costs decreased.

This view generally assumes that the special problems of coupling a fissionable blanket to a fusion driver can be readily solved and that safety and licensing issues will not significantly delay hybrid implementation. However, it is possible that achieving high Q operation for fusion reactors will prove simpler than developing practical and acceptable hybrid reactors, and that

the additional safety issues associated with hybrids may delay their commercialization, relative to that of pure fusion reactors. In our view, such questions should be examined in detail before concluding that hybrids could be developed before pure fusion reactors.

The fourth application of fusion energy, process heat, has received very little investigation. Fusion could supply high temperature heat for a variety of industrial processes, including the iron and steel industry. However, the large thermal ratings (i.e., several thousand MW) characteristic of most fusion reactor concepts are not practical for process heat applications. Unless process industries are more concentrated than is presently the case, maximum reactor ratings would only be a few hundred MW. Most confinement approaches would not be economically viable at this low power rating. [Low power concepts like the Field Reversed Mirror (FRM) would probably be suitable for process heat applications.]

Process heat could be a practical fusion application, however, if some method that could economically transmit high temperature heat for long distances were used. Transmission of sensible heat for even relatively short distances does not appear practical because of thermal losses and high transmission costs. Transmission as stored chemical energy, via the "chemical heat pipe", does not appear practical, however.

The ADAM-EVA concept being investigated by KFA-Julich is an attractive version of this concept. Methane would be endothermically steam-reformed to carbon monoxide and hydrogen using high temperature ($\sim 900^{\circ}\text{C}$) process heat. The CO-H_2 mixture would be transmitted at ambient temperature in gas pipelines for long distances to a network of consumers. The CO-H_2 mixture would be

recombined to form methane over a catalyst at somewhat lower temperatures (~ 500 to 600°C). The exothermic heat of reaction (~ 60 k cal/mole of CH_4) could be used for process heat applications at local sites, and the product methane piped back to the methane/reformer/high temperature heat source. This concept uses relatively well developed technology and appears economically viable even at long transmission distances (~ 100 to 200 km). The ADAM-EVA concept was first proposed with an HTGR (High Temperature Graphite Reactor) heat source, but would work equally well with a fusion reactor heat source. The temperature available with the chemical heat pipe would be suitable for most process heat needs.

The chemical heat pipe would also provide a built-in storage capability for process heat. The reliability required for process heat sources is comparable to that for electric generation, so that direct use fusion heat in a process would require that the reactor have high reliability. Storage of the CO-H_2 synthesis gas reduces reactor reliability requirements, while maintaining high reliability for the process heat delivery.

For the last application, space heat, reject heat from a fusion plant would be distributed at a relatively low temperature ($\sim 100^{\circ}\text{C}$) by a conventional hot water piping system. Much of the space heat demand in Europe is supplied by district heat networks, and it appears likely that such systems will grow considerably in the next few years, both in the U.S. and abroad, due to the rapidly increasing cost of oil and gas.

Hot water can be economically transmitted for long distances (on the order of 100 km) if the delivered thermal power is on the order of 1000 MW. A thermal power of this magnitude would meet the space heat requirements of a small city,

i.e., several hundred thousand in population. However, fusion reactors appear to have no particular advantage over other large heat sources (i.e., coal or nuclear power plants, industrial plants, waste incineration plants, etc.), for district heat applications, except that siting might be easier for fusion power plants as compared to coal or nuclear plants. This could result in shorter transmission distances and somewhat lower space heat costs.

3. FUSION IMPLEMENTATION IN THE U.S. ENERGY SYSTEM

The degree of implementation of fusion in the U.S. energy system will depend on various uncertain factors such as: future U.S. energy demands both for electricity and portable fuels; future U.S. energy supplies, including the availability of imports, the cost of fusion energy, and the costs of competing energy sources; and finally, the time scale for commercialization of fusion.

With so many uncertainties, projections of future energy systems into the twenty-first century must involve many assumptions and subjective estimates. These inherently lead to a wide variability in possible energy futures. This variability is often explicitly dealt with by showing a number of "scenarios" that correspond to different assumptions and estimates, leaving it up to the reader to pick the one that he feels the most likely.

The procedure adopted for this study has been to use long term projections developed by the Energy Information Administration¹ to 2020 AD (the furthest time horizon considered in the EIA studies), with BNL extrapolations for supply and demand to 2040 AD. A reasonable implementation rate for fusion is then assumed, starting with commercialization in 2000 AD for both fusion synfuels and electric power generation. The degree to which fusion satisfies energy demands and displaces other supply modes (i.e., imports, coal derived synfuels, etc.) is then determined.

Figure 3.1 details the U.S. energy system for 1977.² Energy inputs are shown on the left side and demand sectors on the right. The allocation of the different inputs to the various demand sectors is followed through the sequence of preparation, conversion, and transport. This RES (Reference Energy System) clearly shows that the U.S. depends very strongly on portable

REFERENCE ENERGY SYSTEM, YEAR 1977

Figure 3.1. U.S. Reference Energy System (1977).

fuels, both for primary energy input (i.e., as oil and gas) and for final end use form (e.g., transportation fuel, space heat, petrochemicals, industrial process heat, etc.). Electricity, while very important, does not represent the major part of the U.S. energy economy.

Figure 3.2 summarizes projections for future U.S. energy consumption to 2020 AD using five different energy system models. These are¹:

- a. BNL/DJA
- b. ETA/MACRO
- c. FOSSIL 2
- d. LEAP
- e. PILOT/WEM

BNL/DJA (Brookhaven National Laboratory/Dale Jorgenson Associates) uses a coupled economic growth model, the Hudson-Jorgenson Long-Term Inter-industry Transactions Model, with an Energy Model, BNL's Time Stepped Energy System Optimization Model (TESOM), which is a time dependent version of the Reference Energy System shown in Figure 3.1. Optimal levels for future energy system activities are determined on the basis of existing energy systems, deterioration rates and lifetimes, supply and demand elasticities, market penetration rates, etc., as affected by the econometric DJA model which relates consumption, investment, capital, and labor factors to a multi-sector input/output model of the U.S. economy.

ETA/MACRO merges the ETA model, developed by Professor Alan Manne of Stanford, with a macroeconomic growth model (MACRO). The linking occurs through the equilibrium price and quantity of energy in the U.S. economy. The ETA normative optimization model incorporates constraints due to energy demand, supplies, and penetration rates. The MACRO model allows substitution between

capital, labor, and energy inputs. Interfuel substitution and effects on GNP are explicitly allowed for.

FOSSIL 2, developed by the Dartmouth Systems Dynamics Group, is a dynamic disequilibrium model incorporating exogenous decision rules governing the flow of investment, resources, and energy consuming goods. Using differential equations to represent the state determined dynamics of the system, it projects energy production, fuel-specific demands, and prices.

LEAP is the in-house energy systems model for EIA. It is a highly detailed dynamic model of the supply and demand for energy in the U.S. It is also a general equilibrium model operating through a market of decentralized decision making so that optimization occurs within each activity of the network rather than optimizing a single overall function as is customary in linear programming models (e.g., total energy cost for the entire energy system). Cost increases due to depletion are incorporated. Projections of aggregated economic activity and population growth are used to determine sector activity and price elasticity for each end-use service. Perfect foresight of all future prices is assumed, allowing producers to withhold resources or shift production across time to maximize profit.

The PILOT studies used the PPIM and WEM dynamic energy/economic growth models developed by Stanford University's System Optimization Laboratory. WEM is an economic growth model containing a process submodel of energy supply and a variable coefficient input/output industrial system. It was used with the EIA scenario assumptions to produce an initial solution for the more detailed model PPIM. It is a time-phased linear programming model that calculates the projected economic growth to minimize the discounted sum of personal consumption over the period of the scenario.

More detailed explanations of the models and input assumptions are given elsewhere.³ EIA supplied common major input assumptions for the studies. These include: real GNP will grow after 2000 AD at an average of 1.4 percent per year and population growth rate will increase to 0.5 percent per year by 2020 (1977-2000 GNP growth rate is projected at 3.1 percent and population growth rate as 0.9 percent). World oil prices were assumed to rise to \$30/bbl (1978 dollars) by 2000 AD, remaining constant thereafter, and imports were not constrained. The assumed oil prices are probably too low, since OPEC oil prices are near that now. Shale oil was constrained to 1 Quad per year in 1955 but unconstrained thereafter. Estimates for recoverable resources were based on statistical mean estimates for oil and gas by the U.S. GS, DOE estimates for enhanced recovery, and Bureau of Mines coal estimates.

As shown in Figure 3.2, there is quite close agreement between the five projections at 2000 AD and relatively good agreement at 2020 AD. (The Pilot Model projections were not carried to 2020 AD.) All models projected large factors of increase for both coal and nuclear usage. Domestic gas/oil and imports decrease somewhat from 1977 levels, but still remain an important part of the energy system. They are no longer the major part, however, being supplanted by the increase in coal and nuclear. More detailed examination of the domestic production indicates that a large fraction of the domestic oil and gas production in later years is from enhanced recovery, however, rather than conventional oil and gas.

Production estimates for liquid and gas fuels are shown in Figures 3.3 and 3.4. EIA projections are used to 2020; extrapolations to 2040 are made by this study based on the EIA trends shown for the interval 2000-2020 AD. Direct extrapolation is made for Lower-48 and Alaska production of conventional oil and gas, enhanced recovery, shale oil, and imports. Synthetic liquids and gas

Figure 3.2. Projections for U.S. Energy Consumption to 2040 AD (EIA Projections).

Figure 3.3. Production Estimates for Liquid Fuels in the U.S. to 2040 AD.

Figure 3.4. Production Estimates for Gaseous Fuels in the U.S. to 2040 AD.

production in the years 2020 to 2040 is determined by the short fall between cumulative production from all the above sources and total demand for oil and gas, as projected from extrapolations of EIA demand levels. Table 3.1 gives the total U.S. energy supply and disposition, while Table 3.2 gives a more detailed picture of consumption type for the four aggregated sectors (residential, commercial, industrial, and transportation). Consumption in the residential and transportation sectors in the period 2020 to 2040 were assumed to remain equal to that in 2020 AD. For the industrial and commercial sectors, consumption of oil and gas for 2020 to 2040 was assumed to remain essentially the same as in 2020, but electricity, coal, and solar/geothermal demands were assumed to rise at the growth rate characteristic of previous years. Under these assumptions, total oil and gas consumption remains almost constant for the period 2000 to 2040 (Table 3.3). As shown by Table 3.3 and Figures 3.3 and 3.4, however, synthetic oil and gas become the dominant sources of portable fuels in the later years. Consumption of electricity, generated almost wholly by coal and nuclear, and industrial coal usage continues to grow through 2040, however.

Figure 3.5 shows total portable fuel consumption in the U.S. for the interval 2000 to 2040, along with a BNL estimate of the potential fusion synfuel implementation level. The fusion synfuel contribution is given in terms of the quads of primary H_2 energy produced by water splitting. Some of the generated H_2 would be used directly as fuel (e.g., for industrial process heater or H_2 fueled aircraft) and some for chemical production (e.g., ammonia), with the remainder being combined with some carbon bearing material (e.g., coal, CO_2 from the atmosphere or limestone) to make portable carbonaceous fuels (synthetic liquids and gases).

TABLE 3.1

U.S. Energy Supply and Disposition, Quads/Yr.

	Actual	EIA Projections			BNL Projections	
	<u>1977</u>	<u>2000</u>	<u>2010</u>	<u>2020</u>	<u>2030</u>	<u>2040</u>
Domestic Supply						
Coal	15.9	46.9	65.2	78.0	99.3	119.5
Gas	19.6	19.3	15.3	11.4	8.5	5.6
Nuclear	2.7	16.9	29.2	43.6	50.1	56.7
Oil	19.8	24.9	23.2	20.3	17.4	14.9
Other	2.4	5.0	5.9	7.4	9.0	10.0
Total Domestic Supply	60.4	113.0	138.8	160.7	184.3	206.7
Net Gas Imports	1.0	1.0	0.8	0.9	0.8	0.7
Net Oil Imports	18.2	11.0	8.6	7.4	5.0	3.0
Net Elec. Imports	0.2	--	--	--	--	--
Total Supply	79.8	125.0	148.2	169.1	190.1	210.4
Disposition						
Residential	11.1	11.8	11.0	10.4	10.4	10.4
Commercial	6.0	7.9	8.3	9.1	10.0	10.8
Industrial	23.3	43.9	54.1	62.6	71.2	79.2
Transportation	20.6	22.0	22.2	21.5	21.5	21.5
Total End Use Consumption	60.5	85.7	95.7	103.6	113.1	121.9
Conversion Less						
Utility	15.9	34.8	45.4	56.1	64.2	72.5
Synthetics	0.0	1.3	3.8	5.9	9.3	12.5
Stock Change	2.1	--	--	--	--	--
Coal Exports	1.4	3.1	3.3	3.5	3.5	3.5
Total Disposition	79.8	124.9	148.2	169.1	190.1	210.4

TABLE 3.2

U.S. Energy Consumption By Sector, (Quads/Yr.)

	Actual	EIA Projections				BNL Projections ⁽²⁾	
	1977	1985	2000	2010	2020	2030	2040
Residential	11.1	12.0	12.3	11.0	10.4	10.4	10.4
Electricity	2.4	3.8	4.2	5.3	5.6	5.6	5.6
High BTU Gas	5.6	5.7	5.3	3.5	2.6	2.6	2.6
Light Oil	3.1	2.5	2.8	1.9	1.4	1.4	1.4
Solar	0	0	0	0.4	0.7	0.7	0.7
Commercial	6.0	8.3	7.9	8.3	9.1	10.0	10.8
Electricity	1.7	3.5	3.3	5.0	6.3	7.2	8.0
High BTU Gas	2.0	2.4	3.3	2.6	2.3	2.3	2.3
Light Oil	1.1	2.4	0.7	0.3	0.3	0.3	0.3
Heating Oil	1.2		0.6	0.3	0.2	0.2	0.2
Industrial ⁽¹⁾	23.3	39.1	38.6	54.1	62.6	71.2	79.2
Coal	3.8	9.7	10.7	20.0	25.4	31.0	36.0
Electricity	2.6	6.4	6.0	9.9	12.3	15.0	18.0
High BTU Gas	8.8	10.7	10.4	9.7	8.7	8.0	8.0
Light Oil	3.3	12.3	4.8	6.8	7.8	8.0	8.0
Heavy Oil	4.8		6.6	7.2	7.2	7.2	7.2
Solar/Geoth.	0	0	0	0.6	1.3	2.0	2.0
Transportation	20.2	23.3	21.7	22.0	21.5	21.5	21.5
Light Oil	18.8	22.2	19.2	19.5	18.8	18.8	18.8
Heavy Oil	0.9	0.6	1.7	2.1	2.3	2.3	2.3
High BTU Gas	0.5	0.5	0.7	0.6	0.5	0.5	0.5
Total Fuel Use							
Consumption	60.6	82.7	80.5	95.7	103.6	113.1	121.9

(1) Low BTU Gas included in coal

(2) BNL projections for 2030 and 2040 are identical to EIA 2020 projection for residential and transportation sector. Commercial sector differs in more use of electricity. Industrial sector differs in use of more coal and electricity, slightly less use of gas.

TABLE 3.3

Projections of Portable Fuels Use in U.S.

Annual use, Quads

Fuel Form	Year	EIA Projections			BNL Projections	
		2000	2010	2020	2030	2040
<u>Gas Conventional</u>						
High BTU Gas		0.4	1.6	2.7	5.0	8.0
Gas Imports		1.0	0.8	0.9	0.8	0.7
Enhanced Recovery		3.4	3.6	3.0	2.5	2.0
Low BTU Industrial Coal Gas		4.1	6.8	9.1	11.2	13.0
Sub Total		8.9	12.8	15.7	19.5	23.7
<u>Conventional</u>						
Lower 48		13.7	9.7	7.0	5.0	3.0
Alaska		2.1	1.9	1.4	1.0	0.6
Sub Total		15.8	11.6	8.4	6.0	3.6
Total Gas		24.7	24.4	24.1	25.5	27.3
<u>Liquids</u>						
<u>New Conventional</u>						
Coal Liquids		2.6	7.2	11.0	16.6	21.1
Shale Oil		1.8	3.6	5.1	6.0	7.0
Oil Imports		11.0	8.6	7.4	5.0	3.0
Enhanced Recovery		5.4	5.7	4.8	4.0	3.0
Sub Total		20.8	25.1	28.3	31.6	34.1
<u>Conventional</u>						
Lower 48		13.8	9.6	6.6	4.0	2.0
Alaska		4.0	4.3	3.9	3.4	2.9
Sub Total		17.8	13.9	10.5	7.4	4.9
Total Liquids		38.6	39.0	38.8	39.0	39.0
Total Nonconventional (Oil and Gas)

Figure 3.5. Fusion Synfuel Contribution to U.S. Portable Fuels Consumption Until 2040 AD (Normal Implementation Rate).

Determination of the optimum splits for fusion synfuel products is a complicated problem and requires detailed examination with some energy system model such as TESOM, along with development of relative cost and substitutability information. Such an examination is not possible within the scope of the present study. The effect of fusion synfuels on the U.S. energy supply requirements can be estimated approximately by using some reasonable assumptions, however, and the result is shown in Figure 3.6. Fusion synfuels are assumed to displace alternate sources of energy in the following sequence:

1. Oil imports are displaced first, with the fusion produced H_2 converted to liquid fuels by combination with coal. The amount of coal required is reduced by a factor of two as compared to a conventional coal liquids plant, since H_2 and process heat are not generated by coal reactions.
2. After oil imports are displaced, conventional coal liquids are displaced. Again, the fusion product H_2 is converted to liquid fuels by combination with coal, with the amount of coal being reduced as in step (1) above.
3. After all conventional coal liquids are replaced with fusion synfuels, high BTU syngas is displaced. Fusion product H_2 is converted to methane by combination with coal, with the amount of coal being reduced by a factor of three as compared to conventional high BTU gas (methane contains more hydrogen than oil).
4. After all conventional coal liquids and high BTU gas are displaced, fusion H_2 replaces coal for industrial process heat, on a one to one energy basis.

As Figure 3.6 indicates, the implementation of fusion synfuels could cut oil imports to zero shortly after 2010 AD. It would also permit the leveling off of coal usage at a plateau of ~ 80 quads per year, instead of the rise to ~ 120 quads per year by 2040 projected to occur without fusion synfuels. [The total coal usage with fusion could actually be lower than that shown in Figure 3.6, since some of the coal use for electricity generation could be displaced by fusion electric plants.]

By 2030 all conventional coal liquids and syngas production would be zero, with the equivalent portable fuels made by the simpler process of combining coal and fusion produced H_2 [the difficult coal gasification step for producing synthesis gas (CO and H_2) would be eliminated].

Acceleration of fusion synfuel implementation would result in greater reductions in conventional fossil fuel requirements. The implementation curve in Figure 3.5 represents a reasonable market penetration rate, comparable to that for nuclear power. Two commercial plants are assumed to begin operation in 2000 AD, each of ~ 5000 MW(th) capacity, producing ~ 0.1 quad per year of H_2 fuel.

Faster implementation rates should be possible if an all out crash program were instituted. Of prime importance is the achievement of an early as possible commercialization date, since the first two decades of growth must inevitably have a small impact on total U.S. energy requirements, due to the long lead time to design and build fusion reactors. With a crash program and commercialization in 1995, fusion synfuels could supply a large fraction of U.S. portable fuels by 2020 instead of the 2040 date indicated in Figure 3.5.

EFFECT OF FUSION SYNFUELS ON U.S. COAL USAGE & OIL IMPORTS
(NORMAL FUSION IMPLEMENTATION)

Figure 3.6. Effect of Fusion Synfuels on U.S. Coal Usage and Oil Imports Until 2040 AD (Normal Implementation Rate).

Figure 3.7 is based on our judgment of the maximum fusion synfuel implementation rate, based on technological considerations alone. This implementation schedule does not consider limiting factors such as the availability of capital, need to recoup investment in existing plants, and the desire for conservative implementation of new technologies until firmly established.

This faster implementation schedule strongly affects the U.S. energy system by 2020 (Figure 3.8) and dramatically cuts coal use. [Figure 3.8 assumes that the fusion H_2 is substituted directly for oil imports, coal liquids, etc. in the U.S. energy system, and is not combined with coal to form carbonaceous fuels, as was assumed for Figure 3.6.]

A schedule for implementation of fusion reactors for electrical generation is shown in Figure 3.9. This implementation schedule is comparable to that experienced for LWR's, reaching 500,000 MW(e) (approximately one-third of total generation in 2040 AD) forty years after commercialization. An all out crash program could considerably decrease the time required for fusion to significantly impact U.S. electrical generation.

Figure 3.10 shows our judgment of the maximum fusion electric implementation rate, based only on technological factors and not considering limitations due to capital availability, optimum retirement rate for existing plants, and desire for thorough testing of a new technology before making a major commitment to it. Under this maximum implementation schedule, fusion would be providing almost half of the U.S. electricity by 2030, i.e., within three decades after commercialization.

Figure 3.7. Fusion Synfuel Contribution to U.S. Portable Fuels Consumption Until 2040 AD (Maximum Implementation Rate).

**EFFECT OF FUSION SYNFUELS ON U.S. COAL USAGE & OIL IMPORTS
(MAXIMUM FUSION IMPLEMENTATION & USE AS H₂)**

Figure 3.8. Effect of Fusion Synfuels on U.S. Coal Usage, Coal Liquids, and Oil Imports Until 2040 AD (Maximum Implementation Rate).

Figure 3.9. Fusion Electric Contribution to U.S. Electric Generation Until 2040 AD (Normal Implementation Rate).

Figure 3.10. Fusion Electric Contribution to U.S. Electric Generation Until 2040 AD (Maximum Implementation Rate).

As noted earlier, the degree of implementation of fusion, both for syn-fuels and electrical production, will be affected by the relative costs of fusion and alternative energy forms. Table 3.4 gives some projected energy costs (1978 dollars) for significant energy sources that could be competitive to fusion, together with commercial availability dates, potential implementation levels and advantages and disadvantages. Potential costs for fusion syn-fuels and fusion electricity are discussed later in this study. It appears, however, that coal synfuels will be the prime competitor to fusion synfuels and that coal and nuclear electricity will be the prime competitors for pure fusion electric plants. Fusion-fission hybrid reactors appear to be promising sources of fissionable fuel for an LWR fission economy; as such, they might reduce the projected ~ 9 mil/KWH fuel cost, though probably not by a large fraction. The production of oil from shale, though it appears substantially cheaper than coal liquids, will probably be limited by water scarcity and other environmental factors.

Fission electricity appears to be substantially cheaper than coal and is projected to generate more than 50 percent of total electricity in the EIA long term projections. However, social and political factors may drastically limit the growth of fission energy, preventing it from reaching the implementation forecast by the EIA study.

In our view, the principal competitor to fusion appears to be coal, both as a source of liquid and gaseous fuels, and as a primary fuel for the generation of electricity. The key parameter affecting the cost balance between fusion and coal energy will probably be the price of coal. At some breakeven coal cost, the two energy sources will have equal costs; for coal costs above this value, fusion will be cheaper, below this value, coal will be cheaper.

TABLE 3.4

Alternate Long Term Energy Sources to Fusion

<u>Energy Source</u>	<u>Approximate Date for Commercial Feasibility</u>	<u>Cost (1978) ARC() Projections</u> \$/bbl equivalent	<u>Implementation Limits</u>	<u>Comments</u>
<u>Liquid Fuels</u>				
Coal liquids	1990	37 ^(a)	Environmental Effects	Large Resource Base But Potential CO ₂ and Toxic Problems
Oil Shale	1990	24	Environmental Effects	Problems With Lack of Water and Disposal of Waste
Biomass	1990	—	Supply (~ 2 Quads)	Supply is Land Limited
<u>Gaseous Fuels</u>				
Coal-SNG	1990	32 ^(b)	Environmental Effects	Large Resource Base But Potential CO ₂ and Toxics Problems
Biomass	1990	—	Supply (~ 2 Quads)	Supply is Land Limited
<u>Electricity</u>				
Fission	Available		Uranium Resources (Unless Breeder or or Hybrid)	Hybrid Would Extend LWR economy indefinitely
Coal	Available	\$0.040 ^(d)	Environmental Effects	Large Resource Base But Potential CO ₂ Problem
Solar Thermal	2000	\$0.055 ^(e)	Location	Sunlight Availability in Northern Areas May be Limiting
Photovoltaic	2000	\$0.088 ^(f)	Location	Same
Geothermal	Available	\$0.052 ^(g)	Resource Base and Location	Limited to Selected Location in Western States

Notes to TABLE 3.4

All costs in 1978 Dollars

- a) Capital and O&M are \$4.24/10⁶ BTU ⁽³⁾; coal is \$2.30/10⁶ BTU [includes 70% conversion efficiency] ⁽³⁾, 90% capacity factor
- b) Capital and O&M are \$3.10/10⁶ BTU ⁽³⁾; coal is \$2.30/10⁶ BTU [includes 70% conversion efficiency]; 90% capacity factor
- c) \$800/KW(e) ⁽³⁾; fuel = 8.8 mills/KWH ⁽³⁾; O&M = 1.2 mills/KWH; 80% capacity factor
- d) \$738 ⁽³⁾; O&M = 4.17 mills/KWH ⁽³⁾; coal = 2.00 x 10⁶ BTU, 38% conversion efficiency; combined cycle with low/med BTU gasification, 40% efficiency; 80% capacity factor
- e) \$1300/KW(e) capital cost; 3.0 mills/KWH O&M 50% capacity factor (not specified whether storage cost is included in cost estimate)
- f) \$1100/KW(e) capital cost; 3.0 mills/KWH O&M; 26% capacity factor
- g) \$800/KW(e) capital cost; 32 mills/KWH O&M; 80% capacity factor

The above costs are derived from references ^(1,3)

Figure 3.11. EIA Projections of Long Term Energy Costs.

Since coal is a depletable resource, its cost will inevitably rise as cumulative consumption increases. This behavior is illustrated in Figure 3.11, taken from the EIA long term projections¹ of primary energy costs. The relative scarcity of oil and gas resources results in a rapid climb in cost with cumulative production, while the cost of the much more plentiful coal resource rises much more slowly with cumulative production.

Thus it is inevitable at some future point that the cost of coal will be sufficiently high that fusion synfuels and electricity will be cheaper than coal. Cost estimates of fusion H₂ and coal/fusion symbiotic systems indicate that the breakeven coal cost is on the order of \$2 per million BTU (in 1978 dollars), which--according to the cost/supply curve shown in Figure 3.11--would be reached by 2030 AD.

Although the equivalent of a coal OPEC is unlikely, there will probably be strong upward pressure on prices from groups directly benefiting when coal becomes the major U.S. energy source. The coal price increase forecast by EIA from 1977 to 2020 AD is only 50 percent (in constant 1978 dollars). In our view, future coal long term prices could be considerably above these levels, unless a strong competing energy source, such as fusion, acted to keep prices down.

It thus appears that fusion could be a major U.S. energy source by 2020, for synfuels and electricity production. Technically, it can be implemented to important levels by then; economically, it is likely to effectively compete with the principal energy source at that time, coal.

The substitution of fusion for coal energy would also reduce environmental concerns about the effect of CO_2 on world climate, as well as reducing health effects due to emissions of SO_2 , NO_x , and toxic heavy metals. Such benefits are difficult to quantify in analyses of alternate energy options, but are very important.

4. TECHNOLOGY REQUIREMENTS FOR FUSION APPLICATIONS

Reactor Performance Requirements

The various fusion applications require certain technologies and performance levels for the plasma, fusion blanket, and process system. Table 4.1 lists the general reactor performance requirements for the three major applications--electricity generation, synfuel/chemical production, and fissile fuel production.

The highest performance requirements for plasma Q (fusion power/injected power) and the plasma power density will be for pure fusion reactors generating either electricity or synthetic fuels. The high value of the fissile fuel product, as well as the large increase in power from fission reactions in the blanket, make hybrid reactors practical with much lower power densities and Q 's. The required Q values for pure fusion reactors correspond to ignition or near ignition conditions.

Practical thermal power appears about the same for the three applications, on the order of a few thousand MW. Much smaller output levels would be difficult to achieve with most confinement approaches and probably would be uneconomic, while much higher outputs would increase concerns about plant reliability and recovery of investment. The optimum reactor rating for synfuel plants will probably be somewhat greater (about a factor of two) than for electrical or fissile fuel plants, because of the larger total energy demands for portable fuels in the U.S. energy system.

Any fusion fuel cycle should be suitable for electrical production provided it has an acceptable Q and power density and does not result in unacceptable unit costs; given this condition, advanced fuel cycles would probably be more

TABLE 4.1

Reactor Performance Requirements

	<u>Electricity</u>	<u>Synfuels/Chemicals</u>	<u>Hybrids</u>
Power Level	500 1500 MW(e) [1500-4500 MW(th)]	3000-10,000 MW(th)	1500-5000 MW(th)
Q[<u>Fusion Power</u> Injected Power]	> 10	> 10	> 1
First Wall Load, MW(th)/m ²	> 1	> 1	> 0.3
Fuel Cycle	Either DT or Advanced Fuel	DT Fuel; Perhaps Cata- lyzed DD	DT Fuel or Catalyzed DD
Blanket Lifetime	> 3 years	> 3 years	~ 2-3 years
Required Plant Availability	> 0.7	> 0.7	> 0.5
Required Plant Reliability	Very High	Moderate	Moderate
Blanket	Moderate Temp. ($\geq 300^{\circ}\text{C}$)	High Temp. (Either Single Zone or Two Zone Blanket)	Moderate Temp. ($\geq 300^{\circ}\text{C}$)
Reactor Operating Cycle	Continuous Output Preferrable	Continuous or Pulsed Output	Continuous Output Preferrable

attractive than the DT cycle, since radiation damage would be reduced and power generation efficiency could be higher, if direct conversion proves practical.

However, for synfuel and fissile fuel applications, it appears necessary to have a large part of the fusion energy release appear in the form of high-energy (14 MeV) neutrons. In the case of synfuel reactors, the high-energy neutrons can penetrate deeply into blankets, which allows very high process temperatures for efficient synfuel production. In the case of hybrids, the 14 MeV neutrons can generate extra neutrons for fissile fuel production by fast fission of fertile blanket materials (U^{238} or Th^{232}). Although the catalyzed-DD cycle has a mixed yield of high- and low-energy neutrons (about one-half at 14 MeV, with the remainder at 2 MeV), the elimination of the requirement for breeding tritium to replace that burnt in the plasma (which is required with the DT-fuel cycle) makes it potentially attractive for hybrid reactors.

All fusion applications will probably require reasonably high plant availabilities (fraction of the time the plant is on-line), on the order of 0.5 to 0.8, due to the high capital investment for the reactor. As with any electric generation system, fusion reactors connected to the grid will have to have high reliability, with relatively few outages per year. Reliability requirements for synfuel and fissile fuel production plants will be considerably less demanding, since the product can readily be stored off-line. Fluctuations in plant output can thus be readily smoothed out by using available storage to meet demand requirements if the plant shuts down. While high capital cost reactors will have to have high plant factors for economic reasons, they could be allowed to shut down unexpectedly fairly often for short periods (i.e., to start up a balky plasma), if they were not connected to an electrical grid.

Different types of blanket performance are required for each application. The least demanding application is electric generation, since moderate temperature blankets (~ 300 to 500°C) can supply steam for conventional power cycles. Synfuel blankets require high temperature coolant capability, which can be achieved with two temperature zone blankets discussed later in this report. Although such blankets appear feasible, they will be more complex than the lower temperature blankets that can be used for electric generation. It should be noted, however, that two temperature blankets could also be used for electric generation to yield a substantial increase in efficiency.

Blankets for hybrid reactors need only operate at moderate temperatures since electrical generation is secondary to fissile fuel production. However, the requirement of breeding both fissile fuel and tritium, as well as the additional safety concerns caused by fission products will make hybrid blankets considerably more complex than standard fusion blankets.

Finally, confinement approaches that yield a continuous plasma output will be strongly preferred for both electric generation and hybrid plants. This occurs because of the need for constant electric output (considerable thermal storage may be required if the plasma output is non-continuous). For hybrid applications, the large numbers of thermal cycles in the fuel elements associated with a fluctuating plasma output may adversely affect fuel integrity.

Technology for Electric Applications

There has been considerable examination of the technology for fusion electric applications, both in the various reactor reference designs as well as in studies of particular blanket concepts. Accordingly, we only summarize the various technological approaches and do not examine them in detail. A more detailed examination of synfuel production technology is given in the next section since relatively little has been published in this area.

Table 4.2 summarizes the blanket, materials, and power cycle options available for fusion electric generation. Originally, liquid lithium blankets received the most attention. More recently, experiments have demonstrated that bred tritium will rapidly diffuse out of high melting point solid lithium compounds (e.g., LiAlO_2 , Li_2O , Li_7Pb_2 , etc.) As a result, emphasis has shifted to blanket designs using these materials, since corrosion problems are minimized, and the handling and safety problems associated with high temperature liquid metals are eliminated. The most recent commercial fusion reactor design, STARFIRE, for example, uses a Li_2O blanket with helium cooling.

Solid breeder two temperature zone blankets could be coupled to high efficiency power cycles with a potential maximum thermal efficiency of ~ 60 percent.

A wider range of structural materials appears possible with solid breeder blankets than with liquid lithium or fused salt blankets because compatibility and corrosion factors are not limiting. This is an important consideration since finding structural materials that have good performance under the severe radiation damage (and possibly thermal cycling) conditions inherent in fusion blankets is probably the most demanding task in the development of practical blanket/power cycle technology for fusion electric plants.

Technology for Synthetic Fuel/Chemical Applications

The DT fuel cycle appears to be favored for synthetic fuels production. Each DT fusion releases 17.6 MeV, 14.1 MeV as fast neutron energy and 3.5 MeV as alpha particle energy. While alpha particles can radiolytically decompose H_2O , such a process would lead to unacceptable tritium contamination of the hydrogen product.

TABLE 4.2

Electrical Generation Options

<u>Blanket Type</u>	<u>Coolant</u>	<u>Power Cycle</u>	<u>Materials Structural</u>	<u>Options Breeder</u>	<u>Thermal Cycle Efficiency Range Value (Depends on Design)</u>	<u>Comments</u>
1. Solid Lithium Breeder						
a) Single Temperature Zone	Helium	Steam, Direct Cycle Gas Turbine	Austenitic Stainless Steel, Ferritic Steel, High Ni Alloy, Aluminum, Titanium, Vanadium	Be-LiAlO ₂ , Be-LiSiC ₂ , Li ₇ Pb ₂ , Li ₂ O	30-40%	Good Power Cycle Efficiency Requires Relatively High Structural Temperature (~ 500°C)
b) Two Temperature Zone	<u>Inner</u> Helium or <u>Steam Shell</u> Water, HTS* or Helium	Steam, Direct Cycle Gas Turbine, Potassium Topping, MHD	Austenitic Stainless Steel, Ferritic Steel, High Ni Alloy, Aluminum, Titanium, Vanadium	Breeder Dependent on Temp. Level and Coolant	40-60%	High Power Cycle Efficiency Can Be Achieved With Moderate Structural Temperature (~ 300°C)
2. Liquid Lithium Breeder	Helium, Lithium, Potassium	Steam, Direct Cycle Gas Turbine, Potassium Topping	Austenitic Stainless Steel, Ferritic Steel, Titanium, Vanadium, Molybdenum, Niobium	Liquid Lithium	30-45%	Hazard of fires Liquid Lithium Very Difficult to pump Through Magnetic Field, Lithium Modules Subject to Large Pressures in Time Varying Magnetic Fields
3. Fused Salt Breeder [Flibe(LiF·BeF ₂)]	Helium	Steam	High Nickel Alloy	Flibe	35-40%	Low Breeding Ratio (~ 1) High Melting Point

*HTS = Heat Transfer Fused Salt

The short range of alpha particles in solid matter will result in their energy appearing as a heat flux on the first wall surrounding the plasma along with x-rays (Bremsstrahlung) and ions from the plasma. Structural considerations probably will limit the maximum coolant temperature for the first wall to $\sim 500^{\circ}\text{C}$. This relatively low coolant temperature limit will probably restrict its use to electrical power generation.

In contrast, 14 MeV neutrons have a long range in matter and will deposit their energy inside reactor blankets. This unique feature of the fusion neutrons can be used for high efficiency hydrogen production processes. As they slow down, the 14 MeV neutrons cause nuclear reactions, generating high energy gamma rays; eventually, the neutrons will be captured by blanket nuclei, releasing several MeV of additional energy (the precise amount depends on the particular blanket design).

The neutrons (n) and gamma (γ) rays can split water directly by excitation and dissociation of water molecules. Alternatively, the (n,γ) energy could be deposited as heat in very high temperature blanket interiors for thermal water splitting processes. Depending on choice of coolant and materials, interior temperatures could exceed 2000°C , for example, even though the first wall and module structure would be at or below 500°C . The interior region would have to be thermally insulated from the first wall and module structure, however.

Studies of such "two temperature zone" blankets indicate that the equivalent of approximately 60 percent of the total fusion energy can appear as high grade heat in the blanket interior. Heat leakage from the hot interior will be only a few percent of that deposited in the interior. Fusion thus appears to have the highest temperature capability of all the inexhaustible energy sources.

Figure 4.1 summarizes the potential hydrogen production processes using fusion energy. Three temperature ranges are distinguished. In ultra-high temperature range (Mode I, $\geq 2000^{\circ}\text{C}$), one could thermally decompose a process fluid to yield hydrogen, either by the direct decomposition of steam to hydrogen and oxygen or by the decomposition of CO_2 with a subsequent shift reaction to hydrogen. To achieve these high temperatures, direct heating of blanket interiors which do not require heat transfer across intermediate heat exchangers will be required. The interior temperature level is set only by the capability of the inside materials. Mode I energy also could be used to generate electricity with an advanced power cycle (e.g., MHD) at ~ 50 to 60% efficiency (compared with the ~ 35 to 40% for a conventional power cycle). Hydrogen could then be produced by conventional electrolysis at a high-overall efficiency.

The Mode II high-temperature range ($\sim 500^{\circ}\text{C} \leq T \leq 2000^{\circ}\text{C}$) could be used for multi-step thermochemical cycles for hydrogen production,⁴ electric power cycles,⁵ and high-temperature electrolysis.⁶ In the first alternative, a series of chemical reaction steps is driven by high-temperature heat inputs. The complete cycle splits input water into output hydrogen and oxygen, with the reaction chemicals being regenerated and recycled. An example of an attractive option for the second alternative is the closed Brayton gas turbine cycle. The third alternative, high-temperature electrolysis (HTE),⁶ involves the electrolysis of steam at high temperatures using ceramic electrodes and electrolytes. In the HTE process, a large fraction of the energy input is heat, not electricity. This results in a high efficiency for conversion of fusion-to-hydrogen chemical energy.

Mode III energy, at temperatures of $\sim 500^{\circ}\text{C}$ or below, appears useful only for electrical generation by conventional power cycles. Fusion synfuel blankets would be designed to minimize the amount of energy in this mode. Process fluids

Absorber Mode For Energy Absorption in Blanket

- I. (n,σ) Deposition As Heat In Ultra High Temperature Blanket Interior (T ≥ 2000°C)
- II. (n,σ) Deposition As Heat In High Temperature Blanket Interior (500°C ≤ T ≤ 2000°C)
- III. (n,σ) and (α) Deposition As Heat In Blanket First Wall and Module Structure (T ≤ 500°C)
- IV. Direct (n,σ) Radiolysis of Blanket Process Stream

V. n,σ and α Deposition

Modes of Energy Conversion For Hydrogen Processes

A. Thermal Decomposition	
IN	OUT
I	Single Step Thermal Decomposition

B. Thermochemical Cycle	
IN	OUT
II, III	Multi Step Thermal Decomposition of Water

C. Power Cycle	
IN	OUT
Advanced: I, II	Electricity
Conventional: III	

D. Electrolysis of H ₂ O	
IN	OUT
High Temperature Electrolysis: II Electricity	H ₂ + O ₂
Conventional Electrolysis: Electricity Only	

E. Radiolysis	
IN	OUT
IV	Radiolytically Dissociated Gases or Liquids

F. Direct Gasification	
IN	OUT
II	Reaction With Coal

Energy Conversion Examples

Advanced Power Cycles: MHD, Wave Engine, High Temperature Turbine

Conventional Power Cycle: Steam Power Cycle

High Temperature Electrolysis:

Figure 4.1. Potential Processes for Producing Hydrogen Using Fusion Energy.

can also be radiolytically decomposed (Mode IV energy) to produce hydrogen, either directly ($\text{H}_2 \xrightarrow{\text{h}\nu} \text{H}_2 + 1/2 \text{O}_2$) or indirectly ($\text{CO}_2 \xrightarrow{\text{h}\nu} \text{CO} + 1/2 \text{O}_2$, followed by the shift reaction to H_2). However, present knowledge about radiolytic reactions indicates that radiolytic processes for fusion synfuels have too low an efficiency to be practical.

Thermal decomposition (Mode I) is potentially simple and efficient. However, no practical way has yet been found to cool the products fast enough to prevent recombination. Also, blanket materials suitable for long-term exposure to the process gas (a mixture of CO_2 , CO , and O_2) at very high temperature has not yet been demonstrated.

Advanced power cycles such as MHD,⁷ high-temperature gas and steam turbines,⁵ the wave energy exchanger,⁸ and the potassium topping cycle⁹ have been proposed for fusion reactors, with projected thermal cycle efficiencies of ~ 50 to 60 percent. However, in most of these cycles, only the fusion heat extracted at high temperatures (Mode I and II) could be used. Lower temperature heat (Mode III) from the first wall structure would have to be used in separate, lower efficiency power cycles, making the average cycle efficiency for the reactor 5 to 10 percent lower.

Multi-step thermochemical cycles for hydrogen production have been investigated; these have generally assumed that the maximum heat input temperature is $\sim 900^\circ\text{C}$, the level of the fission HTGR (High Temperature Graphite Reactor). No practical pure thermochemical cycle has been found yet; interest has primarily focused on hybrid thermochemical cycles with one of the process steps being electrolytic, e.g., the Westinghouse sulfur cycle.¹⁰ To date, cycle irreversibilities tend to limit overall efficiency to a value comparable to conventional

power generation and electrolysis. The higher temperature achievable with fusion reactors should increase the efficiency of thermochemical processes by reducing the number of steps in the cycle. Even if efficient thermochemical or hybrid cycles are achieved, however, materials and chemical processing problems will be difficult. The process streams are generally corrosive and complex separations are required. Losses of expensive process chemicals such as iodine, bromide, cesium, or bismuth could easily render the system uneconomic.

The remaining process, high temperature electrolysis (HTE), is described next. HTE should have the highest fusion to hydrogen efficiency, ~ 50 to 70 percent, depending on operating conditions and power cycle. HTE cells have operated satisfactorily for thousands of hours at $\sim 1000^{\circ}\text{C}$; ¹¹ while engineering development of large systems would be necessary, no fundamental problems are foreseen. Experiments with blanket materials for HTE/fusion are very encouraging. At present, HTE appears to be the most promising candidate for fusion syn-fuels.

The electrochemical decomposition of water into hydrogen and oxygen is an endothermic reaction requiring both heat and electricity. The efficiency of production of electricity from fusion reactor heat is limited by the Carnot relationship and various irreversibilities in the power cycle. With conventional steam power cycles, electrical generation efficiency will be on the order of 40 percent. Since the heat input component for water decomposition is used directly at essentially 100 percent efficiency, there is a definite advantage to making the ratio of the direct heat input to the electrical energy input as large as possible.

At a temperature T , the input thermal energy equals $T\Delta S$ where ΔS is the entropy change for the reaction. The electrical energy input equals the Gibbs free energy change, ΔG for the reaction, and the sum of these energy changes equals the reaction enthalpy, ΔH .

The energy splits are shown as a function of temperature in Figure 4.2. As temperature increases, the reaction enthalpy remains virtually constant. The Gibbs free energy or electrical energy input, however, decreases with increasing temperature and the thermal energy input, $T\Delta S$, increases. The ratio of thermal energy ($T\Delta S$) to electrical energy (ΔG) increases with electrolysis temperature; this results in higher process efficiency so that more hydrogen product can be generated for a given fusion energy input.

The heat input, $T\Delta S$, absorbed by the HTE cells during electrolysis is supplied from the sensible heat content of the process streams. For practical electrolyzer designs, the steam/ H_2 stream will cool by 100 to 200°C as it proceeds through the electrolyzer.

Figure 4.3 illustrates the type of "two temperature zone" blanket module that will be required to supply high temperature process steam to the electrolyzers. Two temperature blankets were first proposed as a way of using an aluminum structure in fusion blankets to achieve extremely low radioactive inventories.

For HTE applications, the two temperature zone blanket would have a water cooled stainless steel shell at $\sim 300^\circ\text{C}$ and a steam cooled refractory oxide interior at a much higher temperature, e.g., on the order of 1500°C . The HTE process heat modules would comprise approximately 40 percent of the total reactor blanket, with the remaining portion devoted to providing heat for the

FUSION - HTE - SYNTHETIC FUELS
THERMODYNAMICS OF WATER DECOMPOSITION (STEAM)

Figure 4.2. Thermal and Electrical Energy Splits
for High Temperature Electrolysis of Water,
As a Function of Temperature.

Figure 4.3. Two Temperature Zone Blanket Concept
for High Temperature Coolant Processes.

electrical power cycle and breeding tritium. On the order of 50 to 60 percent of the fusion energy incident on the HTE process heat modules would be carried away by the high temperature steam coolant; the remainder would be carried away by the coolant for the low temperature shell and used to generate electricity.

The refractory oxides (ZrO_2 or Al_2O_3) in the high temperature region of the blanket must be stable under exposure to the steam or steam/hydrogen process stream under radiation and thermal cycling conditions. Such materials will fill the interior of the blanket as solid rods or balls, and will also be used as a low density solid block or fibrous thermal insulation between the high temperature interior and the structural shell. Materials compatibility tests in steam and steam/hydrogen carried out at BNL¹² indicate that ZrO_2 and Al_2O_3 show negligible weight loss up to the maximum temperatures studied, $\sim 1500^\circ\text{C}$.

Extensive work has been done on the use of solid electrolytes for the high temperature electrolysis of steam. Major developments in high temperature solid oxide electrochemical cells have resulted from studies of solid oxide fuel cells at Westinghouse Research and Development Laboratories.¹³ The Westinghouse fuel cell design is based on a thin layer electrochemical cell supported on a thick ceramic porous base. This approach permits significant reductions in electrolyte thickness. In earlier designs where the electrolyte was self-supporting, electrolyte thicknesses were large and performance relatively poor. A schematic of the Westinghouse fuel cell is shown in Figure 4.4. This design also serves as the basis for the high temperature electrolyzer since an electrolyzer is a fuel cell in reverse.

Figure 4.4. HTE Cell for High Temperature Electrolysis.
(Westinghouse Design).

For 1000°C operation, the cells are composed of a porous nickel cermet hydrogen electrode, a doped indium oxide oxygen electrode, and a $\text{ZrO}_2 - \text{Y}_2\text{O}_3$ electrolyte which is vapor grown to a thickness of several tens of microns. Typically, current densities in the electrolyte are on the order of 500 mA/cm². The cell is adaptable to mass production, with each component laid down successively in a manner similar to the production of integrated semiconductor circuits.

In order to keep electrode currents within acceptable limits, successive cells along each electrolyzer tube are connected in series. A large number of electrolyzer tubes are then connected in parallel in a large pressure vessel. Typical steam pressures in a high temperature electrolyzer are on the order of 5 to 10 atm.

Brown Boveri, in the Federal Republic of Germany, has tested solid oxide fuel cells for extended periods of time. Single cells have operated for over 34,000 hours,¹¹ and lifetimes of more than five years are expected. This cell uses nickel anodes, lanthanum-nickel oxide cathode, and a 1.2 mm thick electrolyte.

The work on fuel cells has shown that high temperature solid oxide electrochemical cells can be operated at 1000°C. The major problem has been the connection between cells. However, recent developments have made available mixed oxides with all the required properties for the interconnectors. A program is now underway at Brookhaven National Laboratory to test materials in the 1400°C and higher temperature range for electrolyzer components.

Figure 4.5 shows the overall efficiency (fusion energy to hydrogen chemical energy) projected for the HTE process as a function of electrolysis temperature for two values of power cycle efficiency--40 percent, which corresponds to a conventional power cycle and 60 percent, which corresponds to an advanced power cycle using high temperature coolant from the fusion blanket. Efficiencies are expressed for both the lower heating value (LHV - non-condensed H₂O combustion product) and the higher heating value (HHV - condensed H₂O combustion product) of hydrogen. [The heating values for various fuels are usually expressed in terms of HHV.]

HTE offers a considerable gain in efficiency over conventional low temperature electrolysis (HTE), and performance improves as the electrolysis temperature increases. However, quite high efficiency can be achieved at temperature levels where existing materials appear adequate. For example, operation at 1500°C (1800°K) corresponds to an overall efficiency of 52 percent with a standard power cycle and 70 percent with an advanced power cycle. Further increases in electrolysis temperature may not be justified, since the relatively small improvements in efficiency would result in much more difficult material problems.

Further work is needed to more closely define optimum operating conditions and efficiencies, however. At this point, it appears likely that hydrogen can be produced at an overall efficiency in the range of 50 to 70 percent, using high temperature heat from fusion reactors.

HYDROGEN PRODUCTION FROM FUSION REACTORS
HIGH TEMP ELECTROLYSIS (HTE) WITH
CONV. (CP) AND ADVANCED POWER (AP) CYCLE

Figure 4.5. Overall Efficiency (Fusion to Hydrogen Chemical Energy) As a Function of HTE Temperature.

Because of the modifications required in distribution, storage, and end-use utilization, hydrogen probably cannot directly replace a major part of U. S. liquid and gaseous fuels in the next several decades. However, hydrogen generated by fusion reactors could be converted to more conventional synthetic fuels, i.e., SNG, alcohols, gasoline, and oils if it is combined with carbonaceous raw materials such as coal, biomass (agricultural and aquatic) and carbon dioxide (from limestone, natural wells, or the atmosphere). The most readily available and efficient carbon source is coal.

Combining fusion and coal would produce present types of portable fuels, while reducing coal requirements by a large factor, compared to coal-only synfuel processes. This would greatly ease coal production constraints and environmental problems. A long-term evolution to energy systems based on hydrogen and carbonaceous fuels from non-fossil CO_2 sources could then take place.

Present methods of conversion of coal to synthetic gaseous and liquid fuels are summarized in Figure 4.6. For SNG, coal is first gasified with steam to produce CO and H_2 by the endothermic water-gas reaction, with the energy supplied by oxidation of additional coal with oxygen. Some of the CO is then reacted with more steam (water-gas shift reaction) to form H_2 and CO_2 . After removing acid gases (CO_2 and H_2S), the H_2 to CO molar ratio is adjusted to 3/1 and the gases catalytically combined to CH_4 (SNG). More advanced methods catalytically gasify coal with steam to methane and CO_2 ¹⁴ or directly hydrogenate coal to methane (Hydrane and Flash Hydropyrolysis).¹⁵ For liquid hydrocarbons, CO and H_2 can be catalytically combined to hydrocarbons (Fisher-Tropsch Synthesis) or coal can be directly catalytically hydrogenated to aromatic and aliphatic hydrocarbons (H-coal).¹⁶ A third indirect route is to gasify coal and combine CO and H_2 to methanol, followed by catalytical dehydration of methanol to gasoline (Mobil Process).¹⁷

Figure 4.6. Present Processes for Conversion of Coal to Synthetic Gaseous and Liquid Fuels.

In all these processes, the H/C ratio increases from ~ 0.8 (characteristic of coal) to 2.0 for liquid fuels and to 4 for SNG. Ash and other impurities are also eliminated. Most of the coal consumed in these processes is used to generate hydrogen and process heat, so that the coal utilization efficiency (moles of carbon in the product per mole consumed in the process) is relatively low (Table 4.3). Also shown are the thermal efficiencies (the higher heating value of the fuel product divided by the heating value of the coal taken as carbon). These idealized efficiencies assume recovery of all sensible and latent heat. With no heat recovery and actual coal compositions, thermal efficiencies are ~ 20 percent less than in Table 4.3.

Although thermal efficiencies for coal conversion are 70 to 100 percent, coal utilization efficiencies are only 30 to 45 percent for gases and 40 to 60 percent for synthetic liquids. Most of the coal feed is used for heat and hydrogen and turns into the waste material, CO_2 . This wasted carbon can be saved by using fusion reactors instead of coal to produce the needed high temperature steam ($\geq 1000^\circ\text{C}$) and hydrogen.

Figure 4.7 shows processes for synthetic gaseous and liquid carbonaceous fuels using fusion reactors to generate hydrogen (HTE process) and high temperature steam for gasifying coal.¹⁸ The high-temperature steam gasifier (HTSG) utilizes the high temperature steam above 1000°C continuously from the fusion reactor to generate syngas (CO and H_2). HTSG eliminates the need for an air liquifaction plant and increases the capacity of the gasifier. In a fusion/coal process, the required amount of H_2 from the HTE is added to the syngas produced by HTSG. The shift convertor is eliminated and the acid gas removal operation considerably reduced, compared to conventional coal-only synfuel processes. Table 4.3 shows increases in yield for SNG and fusion/coal liquid fuels, compared to coal-only processes for the same coal feed rate. Using only hydrogen HTE units increases

Table 4.3

	<u>Ideal Process Efficiencies</u>	
	Thermal Efficiency	Coal Utilization
1. All Coal SNG Processes		
a) steam-O ₂ gasification and methanation	72	32
b) catalytic gasification	100	44
c) direct hydrogenation	88	39
2. All Coal Liquid Fuel Processes		
a) direct catalytic hydrogenation	93	56
b) steam-O ₂ gasification; methanolation and dehydration	70	42
c) Fischer-Tropsch synthesis	70	42
3. Fusion/Coal SNG Processes		
a) fusion HTSG	78	50
b) fusion HTE* and steam-oxygen	59	69
c) fusion HTSG and HTE*	63	100
4. Fusion/Coal Liquid Fuel		
a) fusion HTE* with direct catalytic hydrogenation of coal	75	100
b) fusion HTE* and HTSG to methanol with subsequent catalytic dehydration	75	100

* Assumes 60 percent thermal efficiency for conversion of fusion HTE to hydrogen.

Figure 4.7. Fusion/Coal Conversion Processes for Production of Synthetic Gaseous and Liquid Fuels.

SNG production by a factor of 2.0. Using both the HTE and HTSG increases production by 3.2, and all the carbon in the coal feed appears in the SNG product. Using HTSG alone increases SNG production by a factor of 2.2. For synthetic liquid fuels, direct hydrogenation with fusion hydrogen increases yield by 1.8 times, while for methanol production followed by dehydration to gasoline, the use of fusion hydrogen increases yield by 2.4 times.

The thermal efficiencies for the fusion/coal systems include the 60 percent efficiency for the fusion/HTE conversion to hydrogen. The overall thermal efficiencies compare to within 15 percent of the conventional all coal processes so that thermal penalty is a minimum.

A comparison of the coal requirements for a conventional synfuel system and a fusion/coal system is illustrated in Table 4.4. Fuel demands are for 1977, and do not include fuels for electrical power generation. Future U.S. demands will probably be substantially higher, even with vigorous conservation. The three synthetic fuel categories are: SNG, to replace natural gas; synthetic liquids for transport, to replace gasoline, diesel, and jet fuels; and other synthetic oil products, to replace oil presently used for industrial process heat, space heat, and petrochemicals. With conventional coal-only synfuel processes, total coal production must be 2180 million tons/year or 3.7 times larger than the current production level of 600 million tons per year. Since present production goes to coal steam power plants and the iron and steel industry which will continue to consume coal, total production would have to be five times the present level.

With a fusion/coal system, added coal production would only be 960 million tons per year for the same synfuel demand. Furthermore, since much of the fuel demand in Table 4.4 could be satisfied by hydrogen or electricity from fusion reactors, the total additional coal requirement would probably only be about 600 million

Table 4.4

Resource Requirements to Meet Synthetic Fuel Demands

	Coal Only	Fusion/Coal
<u>SNG</u>		
1977 Demand*, Quads	14.8	14.8
Coal Consumption, T/year	7.8×10^8	2.6×10^8
Number of 5000 MW(th) Fusion Reactors	-----	116.0
 <u>Synfuel for Transport</u> <u>(Automobiles, Trucks, Aircraft, etc.)</u>		
1977 Demand, Quads	19.1	19.1
Coal Consumption, T/year	8.6×10^8	4.3×10^8
Number of 5000 MW(th) Fusion Reactors	-----	82.0
 <u>Other Oil Products</u> <u>(Industrial Process Heat, Home Heat,</u> <u>Petrochemicals)</u>		
1977 Demand, Quads	11.8	11.8
Coal Consumption, T/year	5.4×10^8	2.7×10^8
Number of 5000 MW(th) Fusion Reactors	-----	51.0
 Total Coal Consumption, Tons/year	2.2×10^9	9.6×10^8
 Annual U. S. Coal Production Required for Synfuels		
 Ratio, 1977 United States Coal Production (6×10^8 T/year)	3.7	1.6

* Does not include oil and gas used for electrical generation (1 Quad = 10^{15} BTU = 1.6×10^8 BBL oil)

tons per year, the present U.S. production level. Coal production probably cannot increase to the degree required for a United States energy system based only on coal. Environmental and economic costs would be very high and the large increase in the coal industry work force would pose serious health and safety problems. Even if such a massive shift to coal could be carried out, a transition to inexhaustible energy sources would still be required in a few decades. A fusion/coal system should allow a more orderly and economic transition to inexhaustible energy sources.

Approximately 250 fusion reactors would be required to produce all the carbonaceous portable fuels now consumed by the United States. Considering the large scale of the United States energy system and the reduction of over 1200 million tons per year in coal production, the number of reactors appears reasonable. In the long term, when CO₂ additions to the atmosphere are prohibitive, carbonaceous synfuels could be produced by catalytically combining fusion hydrogen with non-fossil CO₂ to produce methanol with subsequent dehydration to gasoline and oils. CO₂ could be extracted from the atmosphere by absorption-stripping with dilute carbonate solutions, or carbon could be obtained from biomass (agricultural waste, forest products, etc.). No net addition of CO₂ to the atmosphere would result, regardless of how much synthetic fuel was produced, and the atmospheric CO₂ concentration would remain constant.

Hydrogen production in fusion plants would promote flexibility and easier siting. Hydrogen can be transported by pipeline like natural gas, though the pumping power and transmission costs per kilometer are approximately three times greater. There has been extensive testing of hydrogen in lower pressure distribution lines and gas-line equipment with no deleterious effects. High-pressure pipelines may be satisfactory, but more work needs to be carried out.

Fusion hydrogen could be transported to different sites to be made into various products. Piping fusion hydrogen to mine mouth coal gasification and liquefaction plants would greatly reduce water requirements, a major limitation at many sites. Direct gasification with very high-temperature steam from fusion reactors would require locating a reactor at the coal processing site, though hydrogen could still be piped in. An interesting possibility is the transmission of synthesis gas to industrial sites where CO and H₂ would be combined to methane for distribution to consumers. Hydrogen transmission requires three times the volume flow of gas as with CH₄, with three times the pumping power costs for the same pipeline diameter. Transmitting CO and H₂ would require four times the gas flow rate. Because of the higher molecular weight than H₂, a slightly larger pipeline diameter would be required to keep pumping power losses at usual values. Since pumping power will vary as D⁻⁵, a small increase in pipeline cost will result in acceptable pumping losses. The reaction heat (~50 kcal/mole) would be available at relatively high temperature (~500°C) [similar to the ADAM and EVA chemical heat pipe concept] and could be used locally for power generation and/or industrial process heat.

Production costs for fusion synfuels are difficult to predict. Costs for more conventional coal synfuel processes are still uncertain, even though much is known about their technology. Based on the fusion reactor reference designs for electrical generation that have been carried out, the projected cost of the reactor and associated plant is generally on the order of \$400 to \$800 per thermal kilowatt.²⁰ Fusion synfuel plants should have roughly comparable costs. Figure 4.8 shows a projected cost for synthetic fuels as a function of coal cost, assuming a fusion hydrogen plant cost of \$500/kW(th), a fusion-to-hydrogen efficiency of 60%, and 15% fixed charges on capital investment. Projected O&M costs are also included for both fusion and coal-only synfuels.

Figure 4.8. Projected Costs for Synthetic Fuels as a Function of Coal Cost.

The projected cost of fusion hydrogen is ~\$5/GJ [1 GJ = 0.95 million Btu] and is independent of coal cost. The cost of synfuels from fusion/coal plants will depend on coal cost, since coal is used as a raw material. However, fusion/coal synfuel cost will be much less sensitive to coal cost than synfuels based on coal only, since the former uses considerably less coal. The coal cost at which fusion/coal synfuel becomes cheaper than coal-only synfuel is ~\$50 per ton for SNG and liquid hydrocarbons.

Cost projections are subject to considerable uncertainty because of the many unknown factors involved. However, the trends are valid and it is clear that at some coal cost, fusion synfuels will be cheaper than coal-only synfuels, in addition to being more environmentally acceptable. Present coal costs for long-term contracts are on the order of \$25 per ton. The much greater demand forecast for coal, along with depletion of the lower cost deposits will probably drive up coal costs. It thus appears likely that fusion synfuels could be economically attractive when the first generation of fusion reactors came on-line, i.e., somewhat after the year 2000.

By the time additions to the atmosphere become prohibitive, the primary factors determining synfuel economics will be the relative unit cost of the inexhaustible resources--fission, fusion, and solar--and their efficiency for hydrogen production. The high-hydrogen efficiency that appears possible with fusion should make fusion a major source of synthetic fuels when this occurs.

5. RELATIONSHIP OF FUSION APPLICATION TO CONFINEMENT APPROACH

Over the years, a large variety of magnetic confinement approaches have been proposed as suitable for achieving practical fusion power. These include closed magnetic systems (Tokamak, Stellarator/Torsatron, Reverse Field Pinch, Elmo Bumpy Torus, Tormak) and open magnetic systems (Minimum-B Mirror, Tandem Mirror, Reverse Field Mirror, Multiple Mirror, Linear Theta Pinch, Laser Solenoid, LINUS, SURMAC, etc) for both steady state and pulsed operation.

Tokamak and Mirror systems appear close to achieving scientific feasibility. The reactor design studies carried out on these approaches indicate that some aspects of the necessary reactor technology may prove difficult for practical commercial reactors. Such concerns may in a large part only reflect the greater degree of technical detail examined for these approaches rather than any inherent disadvantage as compared to other confinement approaches.

In this study we have not addressed the relative physics and technological merits of the different confinement approaches except as they specifically relate to suitability for the various fusion applications discussed earlier. We thus make no judgments about the scientific or technical feasibility of the approaches, but only consider whether or not they meet the performance likely to be required for a given application. For example, a fusion approach with an inherently low Q (fusion power/injected power) such as the standard minimum B mirror, probably would not be suitable for electric or synfuel applications but would be suitable for hybrid applications.

Table 5.1 summarizes our assessment of the suitability of the more promising alternate confinement approaches for electric, synfuel, and fissile fuel production applications.

Table 5.1

Suitability of Alternate Confinement Approaches For Fusion Applications
Performance Area

Confinement Approach	Plasma Burn			Reactor Power			Blanket			Q		
	E	S	H	E	S	H	E	S	H	E	S	H
Tokamak	U (Depends on Dwell Time)	A	U (May Affect Fuel Integrity)	A	A	A	A	A	U (Fuel Integrity)	A (For Ignited Plasmas)	A (For Ignited Plasmas)	A
Stellarator/ Torsatron	A	A	A	A	A	A	A	A	A	A (For Ignited Plasmas)	A (For Ignited Plasmas)	A
Reverse Field Pinch	U (Depends on Dwell Time)	A	U (May Affect Fuel Integrity)	A	A	A	A	A	U (Fuel Integri- ty?)	A (For Ignited Plasmas)	A (For Ignited Plasmas)	A
EBT	A	A	A	A	A	A	A	A	A	A	A	A
Standard Mirror	A	A	A	A	A	A	A	A	A	NA	NA	A
Tandem Mirror	A	A	A	A	A	A	A	A	A	A	A	A
Field Reversed Mirror	A	A	A	U (Low Power Output Suita- ble for Small Plants	NA (Power Level Too Low	NA (Power Level Too Low	A	A	A	U (Marginal)	NA (Q Too Low)	A

Table 5.1 (Continued)

Suitability of Alternate Confinement Approaches For Fusion Applications

Performance Area

Confinement Approach	Plasma Burn			Reactor Power			Blanket			Q		
	E	S	H	E	S	H	E	S	H	E	S	H
Linear Theta Pinch	A	A	U (Pulsed Output Affect Fuel Integrity)	NA (Power Level Too High)	A	NA (Fissile Fuel Producers Too High)	A	NA (Two Temperature Zone Blanket Not Feasible)	U (Pulsed Output Affects Fuel Integrity)	A	A	A
Laser Solenoid	A	A	U (Pulsed Output May Affect Fuel Integrity)	A	A	A	A	NA (Two Temperature Zone Blanket Not Feasible)	U (Pulsed Output May Affect Fuel Integrity)	A	A	A
LINUS	A	A	U (Pulsed Output May Affect Fuel Integrity)	A	A	A	A	NA (Liquid Wall Limits Temperature)	U (Pulsed Output May Affect Fuel Integrity)	A	A	A

A = Performance in Acceptable Range

U = Uncertain - Performance May Not Be Acceptable For Given Application

NA = Performance Not Acceptable For Given Application

E = Electric Generation; S = Synfuel Production; H = Fissile Fuel Production

All of the various confinement approaches appear satisfactory for base load electric power generation [power level on the order of 1000 MW(e)] except for the Standard Minimum-B Mirror (Q too low), and Linear Theta Pinch (power level too high). The suitability of Tokamaks will depend on what the characteristics of the burn cycle turn out to be. If the dwell time between burns (i.e., the time to pump out the plasma chamber and reset the poloidal coils for the next burn) is very long, there may be unacceptable variations in electric output from the plant. The Q value ($Q \sim 5$) of the Field Reversed Mirror approach appears marginal for electric production with conventional power cycles, but may be acceptable with a high efficiency power cycle.

For synthetic fuel production, Tokamaks appear quite suitable even if there is a long dwell time between plasma burns, since the storage feature inherent in synfuel production plants will easily smooth out any short time fluctuation in H_2 output due to variations in plasma power.

The other confinement approaches that appear suitable for fusion synfuel production are the Tandem Mirror, Stellarator/Torsatron, Reverse Field Pinch, and EBT. The LINUS concept would not be suitable since it uses a liquid blanket, and cannot achieve the very high coolant temperatures necessary for efficient synfuel production. The Linear Theta Pinch and Laser Solenoid require blankets through which the pulsed magnetic fields can penetrate very rapidly. This appears to require a blanket that is finely subdivided into a large number of electrically insulated segments. The two zone high temperature blankets proposed for fusion synfuel reactors must be relatively large in scale to achieve adequate thermal insulation and are thus probably not suitable for reactor

approaches where the field rapidly varies. Synfuel production blankets with such reactor approaches would have to be of the single temperature zone type and would require operating the first wall and other structures at unreasonably high temperatures.

The Q of Standard Mirror reactors is too low ($Q \sim 1$) for synfuel production; the Field Reversed Mirror has a higher Q ($Q \sim 5$) but this is still probably too low, and the power level appears to be much lower than the optimum power for synfuel plants. Achieving acceptable plant power would require stacking of a very large number of cells, and plant economics would probably not be favorable. The optimum power level for a fusion synfuel plant is probably on the order of 5000 MW(th), which is substantially greater than that for electric generation plants.

Q is a much less important parameter for fissile fuel production, and all the confinement approaches in Table 5.1 would probably have acceptably high Q performance, e.g., Q 's of 1 or greater. All concepts have acceptably high power levels with the possible exception of the Field Reversed Mirror. The relatively low power level of each FRM cell may require stacking an excessive number of reactor cells.

The principle factor that could restrict the use of certain confinement approaches for fissile fuel production will probably be the response of the fuel element to variations in power output from the plasma. Although in principle fluid fissile/fertile materials, e.g., molten salts, could be used in a fusion-fission reactor, virtually all designs assume solid fuel elements to facilitate handling and to enhance fissile breeding rates. Fuel elements in conventional LWR's are quite sensitive to power and temperature variations,

and reactors are operated to minimize the number of thermal cycles experienced by the fuel as well as the rate of rise of power. Generally, reactor fuel elements are brought to full power over many hours. For those confinement approaches involving a pulsed plasma output (Tokamaks, Reverse Field Pinch, Linear Theta Pinch, Laser Solenoid, and LINUS), the total number of power cycles and the rate of change of power in the fuel elements will be far higher than is the case with conventional reactor fuel elements. The integrity of fission fuel under pulsed power conditions will probably have to be investigated in detail before it is clear whether or not fuel performance is acceptable.

In general, for each application, there appears to be a substantial number of promising confinement approaches. Much more detailed analyses and experience with operating systems will have to be accumulated, however, before any definite assessment of the optimum approach for each application could be made.

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